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CONVAIR ASTRONAUTICS

SELECTION OF MATERIALS
FOR CRYOGENIC APPLICATIONS
IN MISSILES AND
AEROSPACE VEHICLES

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SUMMARY

A number of high strength structural sheet alloys, plastics, and thermal insulation materials were subjected to a variety of mechanical and physical property tests over the temperature range of +78°F down to the boiling point of liquid hydrogen (-423°F).

The metallic materials were selected for evaluation largely on the basis of their possession of desirable combinations of properties, including high strength/weight characteristics, weldability, formability, corrosion resistance, and resistance to brittle fracture over the range of temperatures at which data were already available. Since the non-metallic materials are intended primarily for thermal insulation and other non-structural applications, the bulk of testing at cryogenic temperatures was concerned with their physical properties.

The strengths of metals increase in the range of 50% to 100% from +78°F to -423°F. Thus, in those structures which are subjected to maximum loads at cryogenic temperatures, advantage can be taken of higher strengths at low temperatures to reduce their weight by basing design allowables upon low temperature properties. Many metals become embrittled at reduced temperatures and this characteristic must be considered in the selection of materials for cryogenic temperature applications. Of the sheet alloys tested, desirable combinations of high strength, high resistance to brittle fracture, and good weldability are exhibited by the following: severely cold rolled stainless steels such as Types 301, 304, and 310 (although Type 301 appears marginal at liquid hydrogen temperatures), titanium alloy A110-AT, aluminum alloy 5052-H38, and age hardened K-Monel. 20% cold worked Haynes 25 alloy and 40% cold rolled Hastelloy B alloy exhibit good strength and brittle fracture resistant properties at temperatures down to -423°F, but their weldability was not evaluated. Aluminum alloy 6061-T6 has good toughness down to -320°F but exhibits moderate notch sensitivity at -423°F. The high strength aluminum alloys of the 2000 and 7000 series are very notch sensitive at -320°F and at -423°F.

Heat treatable stainless steels which harden by transformation to martensite (AM-355) become embrittled at cryogenic temperatures to a greater extent than do stainless steels which harden by a precipitation mechanism (A-286).

Limited data are presented on the mechanical properties at cryogenic temperatures of some structural plastic laminates and adhesives. Thermal expansion and thermal conductivity data on insulation materials over a range of temperatures are also included, as is general information on the liquid oxygen impact sensitivity of a large number of organic materials, and information on the behavior characteristics of films, elastomers, and plastics at cryogenic temperatures.

INTRODUCTION

The selection of engineering materials for application in missiles and space vehicles involves the consideration of a wide variety of structural metals, plastics, and thermal insulations that must operate over a wide spectrum of environmental conditions. These conditions include high and low temperature, fatigue (caused by both thermal cycling and fluctuating loads), and erosive and corrosive conditions as well as those environmental factors peculiar to space which include low pressure with resultant lubrication and evaporation problems, radiation (ultraviolet, electron, and proton) and erosion due to micrometeorites and molecular impacts. All of these materials problems have been encountered at Convair-Astronautics during the Atlas (1955-) and Centaur (1959-) developmental programs, and have either been solved or are currently under study in test facilities designed and built for this express purpose. Thus the materials problems in future space vehicles represent a natural continuation of those materials studies either completed or currently in progress at Convair-Astronautics.

In the area of structural alloys, a wide variety of high strength sheet materials including cold rolled austenitic stainless steels; aluminum, titanium, nickel, and cobalt base alloys; as well as several heat treatable stainless steels have been subjected at Convair-Astronautics to tests at temperatures ranging down to -423°F to determine their suitability for application in missile and space vehicle systems. These programs were supported in part by the Air Force Atlas and Centaur contracts, but the greater portion was supported by internal company funding which had been allocated to advanced research and development projects. The above alloys were selected for study because they exhibited one or more of the following characteristics: high strength/density ratios; good toughness (i.e., resistance to brittle fracture); adequate weldability; retention of properties at both cryogenic temperatures and moderately high temperatures in the range of 700°F to 1200°F; corrosion resistance; and good formability. In order to obtain optimum strengths levels, the alloys selected for study were either cold worked (cold rolled) or heat treated (age hardened or quenched and tempered) to their highest strength levels commensurate with adequate toughness. In addition, since weldability is of prime importance in the fabrication of these vehicles, alloys were tested in both the base metal and heliarc butt-welded configurations.

The alloys were subjected to tensile testing at 78°F, -100°F, -320°F, and -423°F in both smooth and notched configurations, to yield values of yield strength, tensile strength, elongation, and notched/unnotched tensile ratios (stress concentration factor, K_t=6.3) in the base metal, and tensile strength and elongation in heliarc butt-welded joints. Chemical compositions and other pertinent information on the metallic materials tested are given in Appendix A.

The notched tensile tests were included for study to evaluate toughness, which is a measure of resistance to catastrophic brittle fracture. Toughness is a property of vital importance to the missile designer because his structures are subject to shock type loads which occur during hydraulic hammering, vibration due to rocket engine firing, action of quick-closing valves, etc., and will contain built in stress concentrations of varying degrees of intensity due to welding defects, tool marks, assembly eccentricities, random defects in the metal, etc. These conditions all favor brittle failure, and become even more severe at low temperature in that brittle fracture of many materials is more prone to occur at reduced temperatures.

The severest type of toughness test combines high strain rates, sharp notches, and low temperature, as typified by the Charpy V-notch test conducted at low temperature. Notched/unnotched tensile tests were used in this investigation as an index of toughness since almost all of the data reported upon were obtained on relatively thin sheet material and no fully reliable impact test has yet been devised for thin sheet. The notched tensile sample allows use of sharp notches and low testing temperatures, but does not permit the high strain rates available in the Charpy V-notch impact test. The initial strain rate at the root of the notch is, however, greater than encountered in tests of smooth tensile specimens because of the stress concentration effect of the notches.

The stress concentration factor of 6.3 was selected for use in this investigation because previous axial fatigue tests of complex welded joints on 301 extra full hard stainless steel conducted under the Atlas program had exhibited good correlation with notched/unnotched tensile ratios obtained with this value of K_t over a range of temperatures from +78°F to -423°F. Appendix B presents test data on cold worked stainless steels showing the correlation that has been obtained between the notched/unnotched tensile ratios and the fatigue resistance of complex welded joints. A large body of data has been generated as part of the Atlas and Centaur programs, and shows that less acute notches (e. g., K_t of 2.5 to 3.0) are less discriminatory between tough and ductile materials; in fact, in some cases, tests with this notch acuity on known brittle materials have yielded notched/unnotched tensile ratios of about unity. Thus the less sharp notch tends to show that all materials are tough, when actually some may be brittle under actual service conditions. At the other extreme, however, stress concentration factors of 15 to 18 have been employed on a variety of materials by some investigators, and these tests in general tend to make all materials, including tough ones, appear to be brittle. Thus, a K_t of 6.3 lying midway between these two extremes has proven to be both discriminatory between tough and brittle materials, and to correlate with service behavior, which is the ultimate proof of any laboratory test.

For example, in tests of 5052-H38, 2024-T3, and 7075-T6 aluminum alloys (which are successively more notch sensitive) at -320°F, notched/unnotched tensile ratios determined with a stress concentration factor of 3.0 all lie close to unity, which would be interpreted as meaning that each of these alloys has reasonably good and about equal resistance to brittle fracture. The same tests on the same alloys at -320°F using a K_t of 6.3 however, shows the notched/unnotched tensile ratios for 5052-H38, 2024-T3, and 7075-T6 to be 1.02, 0.99, and 0.86 respectively, which is their true order of toughness, or resistance to brittle fracture, as measured by impact and the NRL G_c (crack propagation) tests.

A final point of interest is that low notched/unnotched tensile ratios frequently occur at -423°F where elongation values are relatively high, and may even be tending to increase. This simply demonstrates that elongation in the smooth tensile test is not a measure of toughness, or notch sensitivity. Until recently, many investigators have been using the terms ductility and toughness interchangeably, when actually they measure two distinctly different parameters. Elongation, which is a measure of ductility, describes the ability of a material to deform plastically under conditions of slowly applied loads in the absence of notches or other stress concentrations. Toughness, which may be measured by Charpy V-notch impact strength, notched/unnotched tensile ratios, and various tear tests, is a measure of resistance to brittle fracture under conditions of impact loading and stress concentrations, such as notches, rivet holes, inclusions, sharp re-entrant corners, etc. Combinations of impact loads, stress concentrations, and low temperature form the severest type of toughness test, and are all present in a Charpy V-notch test conducted at low temperature. The correlation of these variables (i.e., strain rate, notch acuity, and temperature) has been made for steels by Jaffe, et al (1), and these concepts may be extended to other alloy systems.

As a result of these considerations, it is seen that a material may have a large amount of ductility as measured by elongation, yet have very poor toughness as measured by notched/unnotched tensile ratios, Charpy V-notch tests, or crack propagation tests. For example, many of the carbon steels exhibit elongations of as much as fifteen percent in tensile tests at -320°F, yet are glass brittle in impact tests (2). Conversely, some high strength stainless steels may have elongations as low as two percent (which is considered quite low), and yet have excellent toughness as measured by any of the previously mentioned tests (3).

Thus, when considering a candidate material for application in a highly stressed missile structure at low temperature, the designer must rely on toughness data rather than ductility data for an intelligent selection of materials. This is especially true in the case of missile applications, because all conditions favoring brittle failure are present, i.e., high strain rates (vibration of rocket engines, hydraulic hammer, action of quick closing valves, etc.), stress concentrations (spot welds, sharp re-entrant corners, tooling scratches, etc.), high operating stresses because of weight considerations, and low temperatures associated with cryogenic fuels.

Non-metallic materials are finding ever increasing applications in missile systems. Plastics are being used extensively in the Atlas and Centaur missiles, and the properties of plastics over wide temperature ranges (-423°F to decomposition temperatures) have been and are being investigated. Structural plastic laminates consisting of fiberglass, asbestos or Refrasil reinforcement and silicones, phenolics, epoxies, polyesters and Teflon as binders have been studied and evaluated during the past three years for their ablation properties and for their high and low temperature mechanical and physical properties. This background in testing plastics at cryogenic temperatures will be extremely helpful in the design of future space vehicles. Structural plastic laminates and plastic honeycomb configurations have been used in the Atlas and Centaur vehicles for heat shields, equipment pods, fairings, brackets, and insulation. Similar applications will be encountered in future space vehicles and much of the data and experience accumulated in the past three years will be applicable to future space vehicles. Additional work has been done on the effect of cryogenic temperatures on adhesives, plastic foam insulations, plastic films, potting compounds and electrical insulations.

A variety of experimental tests have been performed to evaluate various mechanical and physical properties of airborne components subjected to cryogenic temperatures. The mechanical properties of soldered and brazed joints have been determined in both standard tensile tests conducted at -423°F, and in bend tests following thermal cycling between 78°F and -423°F. In addition, dilatometric tests have been conducted at -320°F on a variety of materials to determine their coefficients of thermal expansion. Further tests have been performed on thermal insulations to determine thermal conductivities, in addition to the mechanical properties mentioned previously. Other studies related to the wetting of various materials by liquid hydrogen have been made.

The scope and content of these experimental programs, to be detailed in the following sections, shows that Convair-Astronautics has been in the forefront of studies pertaining to materials problems in missiles and space vehicles utilizing cryogenic propellants. These studies, many of which were conducted at company expense, have resulted in a broad capability in cryogenic testing, including the procurement and development of test facilities and personnel. In the detailed sections which follow, properties of the more promising materials for application in future space vehicles are reviewed, and pertinent experimental data, obtained in Convair laboratories, are discussed in terms of their application in this type of space vehicle.

COLD WORKED 300 SERIES STAINLESS STEELS

In the cold rolled condition, this alloy class exhibits an outstanding combination of properties which suits it for structural application in missiles and space vehicles utilizing cryogenic propellants. These properties include good strength/density ratios, excellent toughness over the range of -423°F to +800°F, good weldability, good corrosion resistance and excellent formability.

Type 301 cold rolled about 60 percent is the skin material used in the Atlas and Centaur vehicles. As such, it has been subjected to an extremely wide variety of mechanical and physical property tests including mechanical property tests over the temperature range of -423°F to 1000°F, weldability tests involving heliarc butt, seam, and spot welds, and resistance spot welds, stress corrosion tests, thermal conductivity tests, and many others. As a result of these tests the properties of this material are accurately known and thoroughly reliable for applications such as recently proposed long range space vehicles. At present, this alloy is being produced to a Convair specification which requires fractional standard AISI tolerances for thickness, camber, flatness, and surface appearance. These closer tolerances resulting from cold rolling by the Sendzimir process, assure a more uniform product, which in turn improves the design accuracy in such vitally important areas as weight, and stress distribution. These advantages accrued to Convair-Astronautics only after long and continuous cooperative effort with the steel producers, of whom at least four major producers have qualified for the production of sheet to our requirements. Thus the current availability of this special material resulting from this development program would be of direct and immediate benefit to new space vehicle contracts.

This alloy and type 304 ELC* cold rolled 50 percent exhibit excellent low temperature properties, and either alloy would make an excellent skin material for new space vehicles. The mechanical properties of type 301 cold rolled 60 percent between 78°F and -423°F are given in Tables 4, 5 and 6 for gauges .013", .023" respectively, while the mechanical properties of type 304 ELC cold rolled 50 percent between 78°F and -423°F are given in Table 9 for sheet material .012" thick. In addition, type 301 extra full hard has been tested in gauges as heavy as .100 inches, and equally high strengths are obtained at all test temperatures (see Table 7).

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* Extra low carbon

The 301 extra full hard exhibits a tensile strength which increases from about 220 ksi at +78°F to about 330 ksi at -423°F, while the yield strength increases from about 200 ksi to 285 ksi over the same temperature range. This immediately raises the possibility of using the low temperature properties as the basis of design allowables, when the structure is subjected to maximum loading only at low temperature. In the new space vehicles it is recommended that the low temperature properties be used wherever possible, to obtain an increase in yield strength, and consequent weight reduction. This procedure is now used in selected areas of the Centaur vehicle.

The increase in yield and tensile strength in this alloy is accompanied by an increase in elongation from about 5 percent at 78°F to about 20 percent at -320°F, and then by a decrease to between 6 and 14 percent at -423°F. The increase between +78°F and -320°F is due to a change in the nature of deformation between these temperatures. At +78°F, this material deforms by necking over a narrow range, so that the elongation measured over the standard 2 inch gauge length is relatively low, although strain at the necked area is much higher. At -320°F however, this material elongates uniformly over the entire gauge length, with a resulting higher elongation. Between -320°F and -423°F, the occurrence of the austenite to martensite reaction causes the material to fracture in a less ductile manner (i. e., less plastic flow prior to fracture) with a resulting lower elongation.

The product of this reaction, martensite, behaves in a more brittle manner than does the austenite, and its presence in large amounts has a deleterious effect on the notched/unnotched tensile ratio and tensile fatigue properties of complex welded joints, and makes the use of this alloy marginal at -423°F. For example, (see Appendix B) a decrease in the notched/unnotched tensile ratio from 0.99 to 0.92 between -320°F and -423°F is accompanied by a decrease in cycles to failure in axial fatigue tests from 2093 cycles to 633 cycles (at the same stress level of 140,000 psi) between the same temperatures. Thus a moderate condition of embrittlement exists in this alloy at -423°F, and the severity of the service application (stress level, stress concentrations, etc.) will determine if this alloy can be used. For example, Appendix B shows that for a lower stress level in the axial fatigue test (from 140,000 psi to 120,000 psi), the average cycles to failure increase from 633 cycles to 1964 cycles at -423°F. This threefold increase in fatigue life is due to the steep slope of the S-N curve in the low cycle, high stress range.

This condition of embrittlement also manifests itself in the spread of experimental data obtained from repetitive tests. Appendix B shows this effect in the ±3 sigma tabulation of cycles to failure in axial fatigue tests. These limits (i.e., ± 3 sigma) mean that in an infinite series of identical tests, the cycles to failure would fall within the given limits 99.7% of the time. It is seen that both lower temperatures and higher stress levels contribute to more brittle behavior, as indicated by wider ± 3 sigma levels.

Where better fatigue life for a given stress level is desired, a more stable steel (i.e., one in which the austenite to martensite reaction does not occur) would be specified. Such a steel is AISI type 310 CRES, which the Materials Research Group has tested in the 40, 60 and 75 percent cold rolled conditions.

In the 75 percent cold rolled condition (see Table 15) this alloy sacrifices some strength at 78°F as compared to extra full hard type 301 to obtain complete stability. However, the increased strength of 310 at lower temperatures exceeds the room temperature strength of type 301. Thus where the steel is stressed only at low temperature, type 310 imposes no weight penalty where room temperature properties are the basis of design allowables. This stability of type 310 is reflected by the higher fatigue life of this material in the welded joint at -423°F. After 2000 cycles (0-140,000 psi) at -423°F, only one small crack had appeared. Based on prior experience in fatigue tests where final failure occurs after 50 percent or more of the number of cycles at which the first crack initiates, it can be conservatively estimated that the fatigue life of this material will be at least 3000 cycles at -423°F; this compares with 633 cycles for the 301 CRES at -423°F.

A very large body of data pertaining to the properties of type 301 stainless steel in varying degrees of cold work, and welded joint configurations has been accumulated during the Atlas and Centaur programs, and all of these data would be directly applicable to new space vehicle programs. For example, softer tempers of type 301 are used where forming operations must be performed during fabrication. An example is the intermediate bulkhead, of the Atlas, which is formed from gore sections that are cold drawn to shape. Tables 1, 2, and 3 give the properties of type 301 cold rolled between 40 and 50 percent which is used for cold forming, while Table 8 gives the mechanical properties of this steel cold rolled 78 percent. This latter steel was studied for the purpose of defining the range of cold work resulting in the optimum combination of strength and toughness. As a result of this study (4), the range of 55-65 percent was found to be the optimum degree of cold work, to yield tensile and yield strengths of 220 and 200 ksi respectively at 78°F accompanied by a notched/unnotched tensile ratio in excess of unity.

Other studies of this alloy class have pertained to type 304 ELC, which exhibits a somewhat higher notched/unnotched tensile ratio in the [illegible] percent cold rolled temper than type 301 extra full hard at cryogenic temperatures. This steel has the potential of being cold worked an extra 10 to 20 percent, which would bring its strength level up to that of type 301 extra full hard. Type 304 ELC has a maximum carbon content of

0.03 percent, which minimizes carbide precipitation during welding which can cause embrittlement in the heat effected zone. The excellent notched/unnotched tensile ratios (in excess of unity at all temperatures down to -423°F) of this alloy indicate that it would have maximum resistance to brittle fracture. (See Table 9).

Additional studies of the effects of variation in chemistry and cold work at low temperature on the mechanical properties of this alloy class were performed on Type 302, (40 and 60 percent cold rolled) and Type 310, (40, 60 and 75 percent cold rolled). The results of these studies, given in Table 10 through 15, show that the Type 310 is fully stable, as deduced from notched/unnotched tensile ratios, in all tempers down to -423°F, due to its high nickel content (20 percent). However, this alloy does not have the high work hardening capability that Type 301 exhibits. Type 301 derives its higher properties resulting from cold work from two factors; strain hardening of austenite, and conversion of austenite to the stronger martensite. This conversion is promoted by low temperature and high tensile stress, but is completely suppressed in the Type 310 due to its high nickel content which stabilizes the austenite.

Further studies of austenite stability as influenced by chemistry were performed on Type 301-N* steel, cold rolled about 60 percent. The data of Tables 16 and 17 show that this alloy has tensile and yield strengths approximately those of Type 301 extra full hard. However, the lower notched/unnotched tensile ratios at lower temperatures show that this steel is unsuited to cryogenic application due to its relatively unstable austenite, which is converted in large amounts to the more brittle martensitic phase.

Stress corrosion studies of Type 301 extra full hard have shown that this alloy should not be used in conjunction with magnesium alloys, no matter how well painted, coated, plated, or insulated the magnesium may be. The smallest scratch or break in the protective coating allows corrosion products (MgO and $Mg(OH)_2$) to come in contact with the stainless steel, which then undergoes stress corrosion attack. This attack is accelerated by environments such as salt spray, but even less severe conditions allow this attack to occur.

Otherwise this steel exhibits excellent corrosion resistance and requires only periodic washing with deionized water, or coating with corrosion preventive films to guard against corrosive attack. In contact with other alloys such as aluminum, K-Monel, titanium, and other steels, only nominal protective measures need be taken.

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* Normal 301 composition with approximately 0.10-0.15% nitrogen added.

In standard elevated temperature tests, the cold worked austenitic stainless retain their properties to about 1000°F before significant loss of strength occurs. In order to simulate the conditions of rapid heating which occur during takeoff, samples of 301 were subjected to rapid heating tests, where heating rates and stresses could be programmed to simulate these conditions prevailing during takeoff and acceleration. These tests revealed that no loss of properties occurred at temperatures up to 800°F, which is the maximum temperature reached on the Atlas skin.

All of these studies of the 300 series stainless steels have been accompanied by thorough metallographic, x-ray diffraction, and magnetic examinations so that the effect of structure on properties could be measured and evaluated. All of these studies show that either Type 301 extra full hard (currently in use on Atlas and Centaur vehicles) or Type 304 ELC, 50 percent cold rolled or more, would make excellent structural skin materials for new space vehicles.

ALUMINUM ALLOYS

The Convair-Astronautics company sponsored test programs relating to the cryogenic properties of aluminum alloys date back to 1957, when initial surveys of the mechanical and physical properties of aluminum alloys indicated a definite lack of engineering data, especially on welded joints, on all of the common alloys at temperatures below -320°F and on many new aluminum alloys at all temperatures (5). As a result, a comprehensive testing program for determining the mechanical properties from room temperature (+78°F) to liquid hydrogen temperature (-423°F) on the 2000, 5000, 6000 and 7000 series aluminum alloys was initiated and has been in progress for over a year. Also, a study of certain physical properties, such as thermal conductivity and coefficients of thermal expansion as well as corrosion resistance was deemed necessary. As pointed out in the facilities and capabilities brochure, laboratory equipment and facilities essential for determining the very low temperature properties of these materials were procured by company funds and a number of personnel were specially trained to handle cryogenic liquids.

The low temperature mechanical properties of three 5000 series aluminum alloys (5052-H38, 5086-H34, and 5154-H38) have been completed (see tables 18, 19 and 20), and testing is currently in progress on two very promising aluminum alloys, 5083 and 5456. Properties determined included ultimate tensile strength, yield (0.2%) strength, elongation, notched (K_t=6.3) ultimate tensile strength, and notched/unnotched ultimate tensile ratios of the parent metal and ultimate tensile strength, elongation, and weld efficiency of heliarc butt welds.

The 5000 series aluminum alloys are ideally a single phase magnesium-aluminum solid solution type alloy with a face-centered cubic structure, conditions which would indicate good toughness at low temperatures. These alloys derive their strength from cold working, which lends itself to the forming of high strength sheet material, and by the alloying effect of magnesium. Also, they are considered weldable by all commercial procedures and methods, and no post-welding heat treatment or processing is required for good joint efficiency. However, as may be seen in Tables 19 and 20 the toughness (as measured by notched/unnotched tensile ratios) of 5086-H34 and 5154-H38 aluminum alloys decreases significantly between +78°F and -423°F. This result (unexpected for a single phase face-centered cubic structure) has been attributed to chemical impurities in the alloys as witnessed by an appreciable amount of inclusions apparent in the microstructure. As one may see from this type of experience, it is very difficult to generalize concerning properties of materials at cryogenic temperatures. Therefore, in view of these and other such data, several alloys are being investigated to determine the effect of impurities (resulting from normal commercial production) by preparing and testing high purity alloys (obtainable by high purity alloying elements, controlled atmosphere melting, ultrasonic treatment during ingot solidification, etc.). Also, in view of the relatively low strength to weight ratio of the 5000 series alloys as compared to stainless steels or titanium alloys, attempts to increase the strength by a greater degree of cold rolling are being investigated.

Measurements of thermal conductivity and coefficients of thermal expansion are being made at -320 and -423°F. A large number of environmental corrosion studies of aluminum alloys, clad and bare, and their welded joints have been made. Also, corrosion resistance of dissimilar junctions with other structural materials have been determined, and in those cases where a corrosion problem was apparent, suitable organic coatings or electro-plated finishes were developed. Compatibility with liquid oxygen has been tested on an aluminum alloy (6061) and it was found to be impact sensitive at 30 to 70 foot pounds of impact load. It is felt that more testing of this type is necessary; however, it is apparent that a certain amount of impact sensitivity with liquid oxygen exists. The significance of liquid oxygen impact sensitivity as measured by various highly arbitrary methods is subject to considerable discussion.

The low temperature mechanical properties of 2014-T6 and 2024-T3 and -T4 sheet and plate stock are being determined as representative of the 2000 series aluminum alloys. This class of alloys contain copper as their main alloying element and derive their strength from age hardening reactions. These alloys are not generally considered weldable due to weld embrittlement and inherently poor efficiency in the as-welded condition. The tensile strengths (50 to 60 ksi at 78°F, and 90 to 100 ksi at -423°F) are appreciably higher than the 5000 series alloys thereby producing a more competitive strength-to-weight ratio. Results of the low temperature mechanical testing to date indicate that these alloys retain good ductility and toughness in the parent metal to -423°F. Therefore these alloys are considered to be good structural materials at cryogenic temperatures if mechanical joining such as riveting may be used in lieu of fusion welding. (See Table 21).

The 6061 aluminum alloy in the T4 and T6 tempers was chosen as representative of the 6000 series, a class of low alloyed aluminum with copper, magnesium, and silicon. Although this alloy is quite weldable by all general welding techniques and retains good ductility and toughness at low temperatures, the very low tensile strengths (30-40 ksi at 78°F and 50-70 ksi at -423°F) practically eliminate this material for missile use except for special low load carrying applications. (See Tables 22 and 23).

The very high tensile strength aluminum alloys are in the 7000 series, a highly alloyed zinc, magnesium, copper type of alloy which derives its strength from age hardening heat treatments. Alloys 7075, 7079, and 7178 in sheet stock in various tempers and 7075 and 7079 plate stock in the T6 temper were chosen for determining the low temperature mechanical properties. These alloys have ambient temperature tensile strengths from 70 to 90 ksi which makes them most impressive on a strength to weight basis. However no methods of producing fusion welds without inherent embrittlement and very poor joint efficiency have been found. (See Tables 24, 25, and 26).

Results of Convair-Astronautics low temperature mechanical testing programs indicate that the 7178-T6 sheet material is very brittle at low temperatures with notched/unnotched tensile ratios of 0.8 at -320°F and lower at -423°F. Also, the 7075 and 7079 sheet and plate alloys in the T-6 temper are quite brittle at cryogenic temperatures with a notched/unnotched ratio of about 0.85 at -320°F and -423°F. The microstructure of these alloys shows a large number of metallic inclusions, which suggests that the toughness of these alloys may be greatly improved by maintaining higher chemical purity during production of the material. A high purity aluminum alloy, X7275, is being procured for testing to determine purity effects.

Thus the aluminum alloys show the most promise for cryogenic application in those places where compressive loads and hence buckling considerations control the design. In these cases, the tough, weldable 5000 series alloys such as 5456, 5086 and 5052 would be used. In other applications where welding is not required, optimum strength/density ratios combined with adequate toughness would be obtained with 2024-T4 or 2014-T6.

TITANIUM ALLOYS

The titanium base alloys are of major interest for missile and space vehicle application because of their outstanding strength/density ratios, accompanied by good weldability, and excellent corrosion resistance. Convair-Astronautics has been in the forefront of titanium alloy use in missile application, and this work is best typified by the successful development and use of the 6Al-4V titanium alloy in the helium pressurization bottles which form part of the pneumatics system of the Atlas missile. These bottles contain helium gas under high pressure, and are cooled in liquid nitrogen (at -320°F) until just prior to takeoff in order to increase their gas storage capacity. Immediately after takeoff, these bottles are subjected to extreme vibrational loading due to their proximity to the rocket engines, while at low temperature. Thus, this application requires a high order of resistance to brittle fracture, which is possessed by this alloy. For the helium bottle application, the 6Al-4V-Ti alloy is solution quenched and aged to a tensile strength in the range of 155,000 to 165,000 psi.

This developmental program required close cooperation with several firms that manufacture these bottles. The welding schedules, process control, and quality assurance techniques were all worked out with the various vendors until today the process is routine. This knowledge and experience would be of immediate and direct benefit to the design of new space vehicles in those applications where titanium would be specified.

Additional company sponsored work has been in progress for over a year in the evaluation of numerous sheet alloys at temperatures ranging down to -423°F, including A110AT, 6Al-4V, B120VCA, 6Al-4Zr-1V, 7Al-12Zr, and RS 140. (See Tables 28 through 34). Data from the A110AT program is given in Table 27 and it is seen that this alloy exhibits excellent notched/unnotched strength ratios which are especially good at the lower temperatures. This alloy was included in this study because of its all alpha (hexagonal close packed) structure, as well as its excellent strength/density characteristics, and its good weldability. No generalities can be made concerning the behavior of hexagonal close packed alloys at cryogenic temperatures. Although magnesium and zinc (both h. c. p.) tend to be brittle at low temperatures, the 6Al-4V titanium alloy (containing a heat treated alpha + beta structure) has given excellent service at -320°F in the form of helium pressure bottles for pneumatics system pressurization as mentioned above.

Alloy A110AT is characterized by large increases in both tensile strength and yield strength and very small decreases in elongation with decreasing temperature. This large increase in yield strength is of prime importance in missile design, because many designs are based on yield strength rather than tensile strength, and large increases in yield strength at low temperature can be used to advantage in structures which are highly stressed only at low temperature.

However, in most cases where yield strength increases rapidly with decreasing temperature, the toughness of the alloy undergoes a transition from ductile to brittle behavior at relatively high temperatures, depending on chemistry, heat treatment, strain rate, type of test, etc. However, this titanium alloy displays an excellent notched/unnotched tensile ratio down to -423°F, and appears to be a promising alloy for cryogenic application in all respects. It should be noted, however, that this alloy loses strength rapidly at temperatures exceeding 600°F.

The welded joint of A110AT is as strong as the parent metal because this alloy does not respond to heat treatment. Thus material air cooled from the welding (molten) temperature has the same strength as the parent material. In tensile tests of heliarc butt welded joints, fracture occurred in the base metal rather than in the weld metal because the weld had been roll planished, thus increasing its strength slightly by cold work.

On a strength-weight basis, the A110AT titanium alloy (5Al-2.5Sn) is superior to the best steel and aluminum alloys at cryogenic temperatures; as shown in the table below, where the strength-weight characteristics of cold rolled Type 301 stainless steel sheet, 5052-H38 aluminum alloy, and A110AT titanium alloy are shown at +78°F, -320°F, and -423°F.

Alloy	Density lbs./in^3	Test Temp.	Tensile Strength lbs./in^2	Tensile Strength/ Density x 10^{-6}
301 Stainless Steel, 60% CW	0.290	+78°F	217,500	0.75
"	0.290	-320°F	315,000	1.09
"	0.290	-423°F	326,000	1.12
5052-H38 Aluminum Alloy	0.097	+78°F	45,000	0.47
"	0.097	-320°F	60,800	0.63
"	0.097	-423°F	85,500	0.88
5Al-2.5Sn Titanium Alloy	0.161	+78°F	119,000	0.74
"	0.161	-320°F	197,500	1.23
"	0.161	-423°F	245,000	1.52

The other titanium alloys studied are newer alloys obtained through a close working relation between Convair-Astronautics and the titanium producers. The 6Al-4Zr-1V and 7Al-12Zr alloys were selected because of their predominately alpha structure. However, the data of Tables 28 and 29 show that these alloys become notch sensitive at cryogenic temperatures, probably because of the small amount of beta present in their structure and possibly because of high interstitial impurities such as oxygen, hydrogen, nitrogen, and carbon. The same effect is noted in alloys RS140 and B120VCA as shown in Tables 30 and 31, again because of the large amounts of beta present in their structure.

The two alloys that show the most promise for cryogenic applications are the A110AT alloy in the form of sheet at temperatures down to -423°F, and the 6Al-4V alloy in the form of high strength heat treated forgings, down to -320°F. For use at -423°F, however, the 6Al-4V alloy is probably restricted to the lower strength annealed condition. The 6Al-4V titanium in the high strength heat treated condition is undoubtedly too brittle at -423°F to be reliable for use at liquid hydrogen temperature. These alloys are not suited for use at temperatures in excess of approximately 800°F, due to the rapid decay of their strength at higher temperatures.

NICKEL AND COBALT BASE ALLOYS

K-Monel

This alloy finds current usage in cryogenic missile system applications such as liquid oxygen manifolds where complicated shapes must be formed from soft sheet material, and then welded and age hardened to higher strength levels without distortion. This alloy exhibits the typical behavior associated with face centered cubic materials; i.e., large increases in ultimate strength, and smaller increases in yield strength and elongation with decreasing temperature, and in addition has a high welded joint efficiency at all temperatures, as shown in Table 35. Table 35 shows that the toughness of this alloy as measured in the notched/unnotched tensile tests actually increases slightly between +78°F and -423°F. It is believed this behavior reflects the toughness of the matrix, and means that the Ni_x (Ti, $Al)_y$ precipitate which increases the strength of the alloy is present in such a fine dispersion (not visible at 1000 diameters) that it does not adversely effect the toughness of the face centered cubic matrix.

The unetched microstructure reveals the presence of some inclusions at 500 diameters, but the hot rolling and heat treatment have combined to cause these particles to agglomerate, so that no sharp edges are present to act as stress raisers. As a result of these studies at Convair-Astronautics, K-Monel has been found to be a very formable and weldable alloy in the annealed condition, and can be aged to moderately high strengths by a low temperature aging treatment (1080°F) such that little distortion of the part occurs. In addition, this alloy is known to be very corrosion resistant.

This alloy would find application in new space vehicles in such parts as intricately shaped liquid hydrogen and liquid oxygen fuel lines and manifolds.

Haynes 25 (L-605)

This cobalt base alloy has been in use in the form of cold rolled sheet for high temperature applications. However, due to its good response to cold work and its face centered cubic crystal structure which is known to possess good low temperature toughness (as well as good elevated temperature properties) this alloy was subjected to cryogenic tests by Convair-Astronautics. Having a combination of good high and low temperature properties in a sheet alloy suits this material for cryogenic fuel tanks that may be aerodynamically heated during takeoff or re-entry.

This alloy was studied in two tempers; 20 and 40 percent cold worked. The 40 percent cold rolled alloy is too brittle to be a useful structural material, but the 20 percent cold worked alloy possesses a very promising combination of properties which suit it for cryogenic application. The data for these alloys are shown in Tables 37 and 38.

The 20 percent cold rolled alloy is seen to have a tensile strength which increases from about 160 ksi at 78°F to about 260 ksi at -423°F, while the yield strength goes from about 120 ksi between the same temperatures. Elongation remains at about 20 percent at all temperatures. These properties are accompanied by a notched/unnotched tensile ratio which exceeds 0.9 at all temperatures studied. Thus this alloy is seen to combine fairly good strength with good toughness down to -423°F. In addition this alloy retains the major part of its strength up to 1500°F, and a minor part up to 1800°F, as compared to 301 CRES which begins to lose its strength rapidly above 1000°F. For example, Haynes 25 sheet cold rolled 20 percent exhibits a tensile strength of 160 ksi at 78°F, 90 ksi at 1500°F, and 40 ksi at 1800°F , while Type 301 cold rolled 60 percent and stress relieved for 2 hours at 800°F exhibits a tensile strength of 275 ksi at 78°F, 200 ksi at 800°F, and 50 ksi at 1200°F.

The 40 percent cold rolled alloy is exceedingly notch sensitive, having a notched/unnotched ratio below 0.7 at -423°F. This is accompanied by an elongation of less than 4 percent at all temperatures, which causes this temper to be dropped for consideration for low temperature service applications.

Since pure cobalt is known to undergo an embrittling phase transformation at low temperature, (face centered cubic to hexagonal close packed) samples of this alloy which had been subjected to -423°F during tensile testing were subjected to x-ray diffraction studies. Samples soaked at -423°F were studied, and found to contain only the face centered cubic phase, which is further suggestion that this alloy is well suited to low temperature use. Apparently the high percentage of alloying elements cause this reaction to become so sluggish, so as to be non-existant in finite time, although the reaction may be favored from a thermodynamic standpoint. In addition, the degree of cold work introduced into the lattice by cold rolling at room temperature would probably retard this phase transformation at lower temperatures, because the transformation requires an atomic shear movement that would be made more difficult in a strained lattice.

This alloy would find limited application in newer space vehicles at those locations normally exposed to cryogenic temperatures, but which are subjected to temperatures in excess of 1000°F due to aerodynamic heating during takeoff. Due to its unfavorable strength/density ratio, further use of this alloy would be minimized.

Hastelloy B

This alloy, like Haynes 25, is primarily a high temperature alloy that has good corrosion and oxidation resistance. It retains over two thirds of its annealed room temperature yield strength at 1600°F, and in oxidizing atmospheres may be used at temperatures up to 1400°F, which makes it especially attractive for space vehicle applications where aerodynamic heating during takeoff and re-entry present high temperature oxidation problems. For this study, the alloy was tested in the 40 percent cold rolled condition, which increased its annealed room temperature yield and tensile strength values of 58 and 130 ksi to 177 and 191 ksi respectively. The data of Table 36 show that the alloy increases in yield and tensile strength to 240 and 283 ksi respectively at -423°F, while elongation increases from 3 percent at 78°F to 16 percent at -423°F. Of major interest is the trend of notched/unnotched tensile ratio as a function of temperature in Table 36, where the ratio is seen to remain close to 1.10 at all temperatures down to -423°F. This excellent toughness is associated with the high nickel content (60 percent) of this alloy which yields a face centered crystal structure at all temperatures.

The favorable high temperature properties of this alloy are mainly due to the presence of 28 percent molybdenum, which also lends corrosion resistance to this alloy. In addition, this composition has favorable response to cold work, especially in yield strength, which is seen to increase almost threefold with 40 percent cold work. However, molybdenum also contributes an unfavorable factor in density, by causing this alloy to have a density of 0.334 lb/in3, compared to 301 stainless steel which has a density of .29 lb/in3. This effect causes the Hastelloy B to appear in a somewhat more unfavorable light than when considered on a strength basis alone.

This work shows that the nickel base "high temperature" alloys also show promise for cryogenic application, and are not necessarily embrittled at low temperature by the presence of large amounts of solid solution elements such as tungsten, as long as the alpha nickel crystal structure is retained. This alloy appears to have promise for limited applications such as certain exposed surfaces of cryogenic fuel tanks that might become overheated during takeoff or re-entry.

HEAT TREATABLE STAINLESS STEELS

AM 355 Alloy

This alloy was subjected to study by Convair-Astronautics because it is one of the highest strength sheet steel alloys available at the present time, and is finding a variety of room and elevated temperature applications where strength/density parameters are of primary importance. This alloy derives its high strength from a combination of plastic strain (i. e., cold rolling) and phase transformation of austenite to the higher strength martensite. The tempering operation then acts to improve the toughness of the martensite. Upon low temperature testing, as seen in Table 39, this alloy was extremely notch sensitive; in fact at -423°F the specimens broke on the gauge marks, and other places, making the calculation of the notched/unnotched ratio impossible. Although other work in 300 series stainless steels has shown that structures containing some martensite of low carbon ($< .08$ percent) content yield satisfactory notched/unnotched ratios, this study shows that higher carbon (.12 percent in this case) fully martensitic structures are unsuited for cryogenic applications.

It is possible, however, that this alloy and others of its class such as AM 350 may have better low temperature toughness (accompanied by lower tensile strength) if the heat treatment is such as to yield more austenite in the martensitic matrix. This is caused by the fact that austenite possesses a face centered cubic structure which is known to be tough at low temperature, whereas the martensite has a body centered tetragonal structure which is known to be brittle at extremely low tempers, expecially in the higher carbon ranges. Tests of AM 350 and AM 355 subjected to various heat treatments are currently in progress.

A 286 Alloy

This alloy was included for study as a representative of the age-hardenable, high strength, heat treatable stainless steel alloy class. The alloy was studied in the annealed and two heat treated conditions. One of these heat treatments was the standard 1325°F, 16 hours, air cool, while the second was on 1100°F for 16 hours, air cool (both aging treatments were preceded by a solution anneal of 1800°F, 30 minutes, air cool).

Table 40 shows that this alloy suffers from a low yield strength, and a moderately low notched/unnotched tensile ratio at low temperature. Otherwise this alloy behaves much like a typical face centered cubic alloy. The anomalies noted appear to be caused by the tendency of this alloy to have a very low rate of work hardening which is probably due to its high nickel content (25 percent) even at low temperature. Thus this alloy at -423°F in the annealed state is capable of yielding at about 100 ksi, and then elongating over 50 percent while the tensile strength goes to only 200 ksi. This behavior also occurs to some extent in the notched tensile coupons, where some plastic flow was seen to occur at the root of the notch, yet little increase in tensile strength occurred, with the result that a low notched/unnotched ratio was obtained.

The age hardened alloys behaved the same way qualitatively, but had higher tensile and yield strengths and lower elongations. One significant fact was however, that the samples aged at 1325°F exhibited higher notched/unnotched ratios than either the annealed or aged at 1100°F samples. This occurrence was caused by the relatively low F_{tu} (caused by the higher aging temperature), and the relatively high notched tensile strength, which also resulted from the higher aging temperature.

SOLDERS

Soldered joints have been commonly employed in many missile electrical systems, such as telemetering, guidance, and control units. Environmental conditions experienced throughout a missile's life requires that many of these soldered joints withstand temperatures from nearly -400°F to possibly as high as 300 to 500°F as well as certain types of radiation, and high vacuum conditions. Choice of a fully reliable solder depends upon a soldered joint's particular service conditions; however, sufficient mechanical and physical property data on soft and intermediate solders were not available to make a fully reliable selection. Therefore a comprehensive testing program whose purpose was to determine the mechanical properties of solders at room and subzero temperatures was undertaken. The following data are a result of this program:

Ultimate Tensile Strengths of Soldered Joints*

	+78°F	-320°F	-423°F
50 Sn-50Pb	**13,600 psi	21,700 psi	26,600 psi
35 Sn-65Pb Soft Solder	13,600 psi	16,800 psi	18,500 psi
Indalloy #5 Intermediate Solder (25% In. with Sn and Pb)	7,500 psi	14,300 psi	21,200 psi

*Joints were prepared using 1/4" diameter brass rod.

**Average of three tests each.

In addition to the tensile properties which are reported above, work is in progress to determine the shear and impact values of parent solders and soldered joints as a function of temperature.

Solders which will be tested include 60 Sn-40 Pb; 35 Sn-65 Pb; 20 Sn-80 Pb ; 1.5 Ag-1 Sn-97.5 Pb; Indalloy #1; and Indalloy #5. Corrosion and compatibility studies are also being made on a variety of soldered joints.

PLASTICS, INSULATION, AND OTHER NON-METALLICS

Plastic laminates are normally employed in the Atlas and Centaur because of their inherent advantages; i. e., high strength to weight ratio, high percentage strength retention at intermediate temperatures (300°F - 800°F), low thermal conductivity, good low temperature mechanical properties and good weatherability.

At present there is an active program at Convair-Astronautics to determine the tensile properties of structural plastic laminates from room temperature down to liquid hydrogen temperature (-423°F). This program encompasses the materials normally utilized in the Atlas and Centaur vehicles. Tensile data of high temperature phenolic-fiberglass laminates conforming to MIL-R-9299 Type II Class I have been run at 78°F, -320°F and -423°F, and average values for ultimate tensile strength and modulus of elasticity in tension are recorded below:

TEMPERATURE	AVERAGE TENSILE STRENGTH	AVERAGE TENSILE MODULUS
78°F	44,380 psi	3.47×10^6 psi
-320°F	70,500 psi	4.66×10^6 psi
-423°F	70,250 psi	3.58×10^6 psi

Additional tensile testing of plastic laminates utilizing fiberglass reinforcement and polyester, silicone, epoxy and Teflon binders has been initiated. Low temperature testing of the MIL-R-9299 material in flexure, shear, compression and bearing has also been initiated.

Most of the structural plastic parts in the Atlas and Centaur utilized a sandwich type of construction: i. e., a phenolic-fiberglass core with phenolic-fiberglass laminate faces. This has the added advantage of a high stiffness to weight ratio. In areas where insulation is required to avoid excessive boil-off of cryogenic propellants, plastic composites of phenolic-fiberglass laminate faces and polyurethane foam core are being employed. A test program originating in May, 1959, was run to determine optimum materials for the Centaur liquid hydrogen tank insulation. More than fifty (50) sandwich panels were constructed and tested. These panels utilized various plastic foam cores, various impregnated-fiberglass laminates and numerous adhesives. The test panels were loaded in simple beam bending under two point loading and the outer face was exposed to a prescribed heat flux-time cycle simulating the "in-flight" aerodynamic heating. The most promising materials are being subjected to further studies which include: high temperature shear testing, thermal conductivity and thermal expansion determinations, and flexure and shear testing of panels with one face at cryogenic temperatures and the other face at 575°F. This type of program has resulted in a type of insulation panel which combines the use of high temperature-resistant outer faces, over-expanded foam core, Freon blow polyurethane foam, and high and low temperature adhesives. This type of background can be directly applied to new space vehicles.

The requirement for low density thermal insulation has continuously been a problem in the Atlas and Centaur vehicles. This type of insulation is required for the liquid oxygen lines; the Centaur liquid hydrogen tank; the forward, aft and intermediate bulkheads of the Centaur; the Atlas intermediate bulkhead; and insulation for electronic packages. Convair-Astronautics has investigated the available plastic foams and is actively engaged in the mechanical and physical property testing of these foams from room temperature down to -423°F. In the past three years thermal conductivity testing has been conducted on insulating materials from -100°F to +300°F (see Table 41). These data are being supplemented by additional testing at cryogenic temperatures. Convair-Astronautics is presently running thermal conductivity values of plastic foams at -320°F (see Figure 3) and a liquid hydrogen thermal conductivity apparatus is in the last stage of fabrication. There is also an active program being conducted at Convair-Astronautics on the determination of thermal conductivity measurements for plastic laminates, plastic honeycomb, and composite structures from room temperature to -423°F. Various other insulating systems (structural and non-structural) have been investigated. These include the vacuum type insulating systems containing powders, fiberglass material, or aluminum foil-paper composites; and non-vacuum systems of fiberglass batting, ceramic foams and impregnated aluminum silicate laminates.

In order to design composite structures of dissimilar materials it is essential to know the thermal expansion of each of the materials over the operating temperature range. In the past Convair-Astronautics has been able to generate data on thermal expansion from -100°F to +1800°F, and this range has now been extended to -320°F. The capability is now in the process of being extended still further to -423°F. Typical expansion curves of phenolic-fiberglass laminates and polyurethane foam over the -320°F to +75°F are given in Figures 4-9. This program has been expanded to include adhesive and sandwich structures along with the laminates and foams now being tested.

Some of the applications in the Atlas and Centaur in which low density plastic foams are being utilized require the foam to carry some mechanical loads. Shear tests of these foams are being run from room temperature down to -423°F. Initial testing in this area indicate slight increases in ultimate shear and shear modulus values at -320°F over the corresponding values obtained at room temperature. This program will also be extended to tensile, compression and flexural testing of foams from +78°F to -423°F. The effect of long time storage on the mechanical and physical properties of plastic foams is also being investigated. This availability of test equipment, the background of data and the experience of the personnel would be of extreme value in the insulation problems which would be encountered in new space vehicles.

Convair has anticipated future problems associated with structural adhesives at cryogenic temperatures, and has initiated a company funded program to investigate the lap-shear, butt-tensile, impact, and peel properties of adhesives covering the range of +78°F to -423°F. This program covers the following adherends: stainless steel, aluminum, titanium, phenolic laminates and combinations of these adherends. Initial testing with 1/2" lap joints of .020" 301 CRES bonded with a modified epoxy adhesive has resulted in low temperature lap-shear values much higher at cryogenic temperatures than any reported by the National Bureau of Standards (WADC Technical Report 59-250). These values are listed below:

TEMPERATURE	AVERAGE LAP-SHEAR STRENGTH
78°F	5,810 psi
-100°F	7,790 psi
-320°F	6,020 psi
-423°F	6,730 psi

Preliminary testing of polyurethane adhesives at -320°F and -423°F has been completed. Polyurethane adhesive has been used successfully in bonding polyurethane foam to itself, polyurethane foam to stainless steel, and phenolic-fiberglass laminate to itself. In all cases the adhesive withstood the extreme low temperatures with no apparent embrittlement. When bonding polyurethane foam to itself, the resulting bond was stronger than the polyurethane foam. A sample of foam (12" x 2 1/2" x 1/2") was bonded to a 36" welded tensile specimen of 310 cold rolled -60% stainless steel using polyurethane adhesive. The specimen was cycled between 0 and 140,000 psi approximately 5-6 times per minute while immersed in liquid hydrogen. After 1700 cycles the foam had cracked but the adhesive remained intact. Polyester adhesives have also been evaluated for use in bonding Mylar to Mylar and Mylar to stainless steel and have successfully withstood repeated cycling from 0 to 120,000 psi at -423°F.

Silicon crystals and ceramic wafers were bonded to .012" 7075Al for evaluation in solar battery applications. Polyester, polyurethane and cyanoacrylate adhesives were evaluated for this application by repeated cycling of the bonds from +78°F to -320°F. Only the cyanoacrylate adhesive failed as a result of thermal shock.

Epoxy, modified epoxy, polyurethane, polyester, and rubber base adhesives were used in bonding polyurethane foam to 301 CRES. Cycling from +78°F to -320°F resulted in failure of the epoxy, modified epoxy and rubber based adhesives as a result of thermal shock and embrittlement of the adhesive. Samples of phenolic-fiberglass laminates were bonded to themselves and to stainless steel utilizing epoxy, polyurethane, and modified epoxy adhesives. These bonds were cycled from +78°F to -423°F with no failures as a result of subsequent manual impact and flexure.

A sandwich panel consisting of aluminum honeycomb and phenolic-fiberglass faces bonded with a phenolic-epoxy, glass supported adhesive was cycled for 10 hours between -420°F and -320°F, and no trace of deterioration in the skin to honeycomb bond was found. The same sample was subjected to crushing and bending forces well beyond any service loads without failure.

Plastic films and gasketing materials have also been extensively investigated at -320°F and -423°F as a result of materials testing for the Atlas and Centaur vehicles. Of the many films tested for flexibility at cryogenic temperatures Mylar, Teflon and Penton showed the best properties. Exhaustive testing has been conducted on Mylar and the bonding of Mylar for cryogenic applications. Evacuated bags have been successfully fabricated utilizing Mylar, and this type of bag can be used in conjunction with fiberglass material to make an excellent low temperature insulating system. Mylar bags have also been tested in the laboratory for use as "zero g" fuel propulsion bags. The use of Mylar for replacement of the non-structural stainless steel section of the intermediate bulkhead of the Atlas and Centaur missiles has been investigated and appears feasible. Mylar film has been successfully laminated, and these laminates successfully withstood cycling from +78°F to -320°F.

Convair has in the past done extensive testing of fluorocarbons and filled fluorocarbons for use in gaskets and lip seals. A testing program is in progress now to evaluate gaskets in liquid hydrogen to determine the molecular diffusion through the gasket, the load-deformation properties and the particle shedding properties. Recent tests indicate that Teflon impregnated asbestos gaskets coated with a Teflon enamel met the 175 micron maximum particle size criteria whereas all other fluorocarbons and filled fluorocarbons tested failed to meet this particle size shedding criteria.

Convair-Astronautics is also in the midst of a company funded development program for modifying fluorocarbons for use at cryogenic temperatures. The objective in this program is to improve low temperature mechanical and physical properties of fluorocarbons by means of modification of filler materials, heat treatment, and pre-stressing techniques. Mechanical and physical properties will be determined over the temperature range of +75° to -423°F on specially formulated and processed fluorocarbon plastics. X-ray, infra-red, and visible light analyses will also be performed to investigate the crystallinity of these materials at room temperature and the effects of formulation and processing techniques on crystallinity.

In direct support of the Atlas and Centaur programs liquid hydrogen and liquid nitrogen testing of potting and casting compounds, electrical insulation and small components have been accomplished. The thermal contraction of Teflon coated wire was investigated. It was found after immersion that the shrinkage of a copper braided conductor tightly sheathed in Teflon was only 1/2" for a 16' length at -320°F and approximately 3/4" for a similar length at -423°F. Furthermore, insulation deterioration testing demonstrated that the material retained its dielectric properties after low temperature cooling and flexing. Silicone rubber insulation was found to be insensitive to impact loads up to 30 inch pounds at -320°F. PVC potting compounds were found to be fragile and contracted from the enclosure walls at -320°F. Other silicone rubber and epoxy compounds were found to crack at -320°F. Additional testing has been conducted on quick disconnects, clamps, brackets, couplings, etc.

A number of silicone rubber and Teflon cushioned clamps have been subjected to temperature cycling, mechanical flexing, and slight to moderately severe impact loading at +78°F, -100°F, -320°F and -423°F. All of the rubber cushions failed in a glass brittle fashion upon cycling, flexing, or impacting at both -320°F and -423°F. All of these failed after four temperature cycles while in an unloaded condition. It was found, however, that thick sections (0.50 inch or heavier) of silicone rubber were able to withstand temperature cycling and the combination of temperature cycling and impact at the cryogenic temperature. Teflon (.020") cushioned clamps withstood the temperature cycling but failed upon moderate impact loading at -320°F. Thicker Teflon sections (.050-.100) were able to withstand all the test conditions.

One of the inherent problems in using liquid oxygen as an oxidizer in a propellant system is the impact sensitivity of most organic materials and some metals when in contact with liquid oxygen. For the past three years Convair has run hundreds of liquid oxygen impact sensitivity tests. The test method conformed initially to the procedure set up by the LOX Lubricants Standards Committee, and more recently the testing has conformed to the standardized test method of the Ballistic Missile Division of the Air Force. Table 42 contains test data obtained on lubricants. Other data on the liquid oxygen impact sensitivity of structural plastics, gasket materials, paints, inks, solvents, insulations, adhesives, sealants, plastic films, etc., have not been included because of the large volume of data and the very limited use of this specific type of data. These data and the ability to do immediate testing on new materials will be extremely valuable to newer space vehicle programs.

The experience that Convair-Astronautics has gained in the testing and use of non-metallic materials at low (-423°F) and high temperatures (300°F-1200°F) will be of great value to new space vehicles. Convair-Astronautics has also considerable background in the ablation properties of materials. For the past three years plastics, metals and ceramics have been exposed to rocket motor exhausts (5500°F, Mach 3) and the ablation rates of various materials have been determined as a function of the fabrication variables of the material. Ablation rates for structural plastic laminates have been determined as a function of resin content, laminating pressure and fiber orientation. There is a continual literature survey carried out at Convair on the mechanical and physical properties of non-metallics, and this has made Convair fully aware of what is being done and what type of information is still required. This type of broad background in the cryogenic and high temperature properties of structural plastics, adhesives and insulations will be required in designing structural or non-structural insulation panels for future space vehicle propellant tanks. It will be extremely valuable in designing insulation bulkheads, structural plastic adapters, heat shields, etc. Convair-Astronautics' experience in gasket materials, potting compounds, electrical insulation, etc., will be extremely valuable in the design of hydraulic, pneumatic and electronic systems of new space vehicle systems.

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TABLE 11

MECHANICAL PROPERTIES OF 60 PERCENT COLD-ROLLED 302 CRES[a]

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED* T. S. ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	181	206	2	222	
	"	179	207	3	224	
	"	180	206	4	220	
	"	176	203	3	221	
	"	176	204	2		
	Average	178	205	3	222	1.08
-320°F	Long.	229	308	28	283	
	"	229	307	29	285	
	"	-	308	29	281	
	"	221	308	28		
	"	226	306	29		
	Average	228	307	29	283	.92
-423°F	Long.	241	292	15	275	
	"	257	299	28	278	
	"	249	292	15	282	
	Average	249	294	20	278	.95
-423°F	Tran.	268	318	3	259	
	"	250	311	11	257	
	Average	259	315	7	258	.82

*Notch "A" K_t= 6.3

[a] Sheet Material .020" thick; produced by Allegheny-Ludlum Steel Co., Heat No. 84204

TABLE 21

MECHANICAL PROPERTIES OF 2024-T3 ALLOY

0.025" Sheet, Alcoa Aluminum Co., QQ-A-355

Test Temp.	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched Tensile Strength ksi	Notched/Unnotched Tensile Ratio
+78°F	Long.	47.8	67.8	17.5	59.9	
	"	47.5	68.1	18.0	59.8	
					60.8	
	Average	47.7	68.0	17.8	60.2	.89
+78°F	Tran.	43.8	66.2	18.5	62.6	
	"	43.9	65.4	18.5	63.1	
	Average	43.9	65.8	18.5	62.9	.96
-320°F	Long.	61.0	86.1	22.0	76.6	
	"	61.4	87.8	22.5	76.6	
	"	60.2	87.2	21.5	75.4	
	Average	60.9	87.0	22.0	76.2	.88
-320°F	Tran.	56.1	83.2	22.5	75.4	
	"	54.9	83.5	22.5	73.9	
	Average	55.5	83.4	22.5	74.7	.90
-423°F	Long.	-	109	19.0	88.3	
	"	70.9	110	14.0	84.8	
	"	75.2	112	19.0	95.2	
	Average	73.1	110.	17.3	89.4	.81
-423°F	Tran.	68.4	106	19.0	85.4	
	"	69.0	107	17.0	88.2	
	Average	68.7	106.	18.0	86.8	.82

TABLE 25

MECHANICAL PROPERTIES OF 7178-T6 ALLOY

.020" Sheet, Kaiser Aluminum Co.

Test Temp.	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched Tensile Strength ksi	Notched/Unnotched Tensile Ratio
+78°F	Long.	72.0	82.1	6.0	85.4	
	"	71.7	82.7	7.5	82.0	
	"	76.8	84.0	10.0	86.6	
	"	78.9	85.4	9.5	87.7	
	Average	74.9	83.6	8.3	85.4	1.02
+78°F	Tran.	76.1	83.5	8.5	81.9	
	"	76.1	83.1	8.5	85.9	
	"	77.9	84.8	7.0	84.9	
	Average	76.7	83.8	8.0	84.2	1.00
-320°F	Long.	83.8	95.0	3.0	73.2	
	"	83.3	95.6	3.5	61.5	
	"	88.0	99.0	3.5	62.2	
	"	91.0	101.0	3.0	64.7	
	Average	86.5	97.7	3.3	65.4	.67
-320°F	Tran.	85.3	94.6	3.0	54.3	
	"	86.6	95.6	2.0	59.4	
	"	85.7	97.9	3.0	61.6	
	Average	85.9	96.0	2.7	58.4	.61

TABLE 26

MECHANICAL PROPERTIES OF 7178-T6 ALLOY

0.036" Sheet, Kaiser Aluminum Co.

Test Temp.	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched Tensile Strength ksi	Notched/Unnotched Tensile Ratio
+78°F	Long.	82.4	90.2	12.0	91.4	
	"	82.6	89.6	11.5	93.3	
	"	83.0	90.0	12.0	90.7	
	Average	82.7	89.9	11.8	91.8	1.02
+78°F	Tran.	79.9	90.2	11.0	79.5	
	"	80.1	90.5	11.5	88.5	
	Average	80.0	90.4	11.3	84.0	.93
-423°F	Long.	112	122	1.5	68.3	
	"	114	125	2.5	57.5	
	"	108	122	2.0	61.2	
	Average	111	123	2.0	62.3	.51
-423°F	Tran.	110	125	3.0	56.9	
	"	109	123	3.0	54.1	
	Average	110	124	3.0	55.5	.45

TABLE 28

MECHANICAL PROPERTIES OF Ti-6Al-4Zr-1V ALLOY

(0.090" Sheet, Heat V - 1166, Mill Annealed Condition)

Test Temp.	Direction		Yield Strength 0.2% Offset psi	Smooth Tensile Tests: Tensile Strength psi	Smooth Tensile Tests: % Elong.	Notched Tensile Strength psi	Notched/Unnotched Tensile Strength Ratio
+78°F	Long.		137,000	142,000	16.0	173,000	
	Long.		136,000	141,000	16.5	173,000	
		Average	136,500	141,500	16.3	173,000	1.22
+78°F	Trans.		137,000	139,000	16.0	173,000	
	Trans.		136,000	139,000	16.5	173,000	
		Average	136,500	139,000	16.3	173,000	1.24
-320°F	Long.		215,000	227,000	10.5	186,000	
	Long.		-	227,000	9.0	184,000	
	Long.		207,000	228,000	12.0		
		Average	211,000	227,300	10.5	185,000	0.82
-320°F	Trans.		217,000	226,000	11.5	169,000	
	Trans.					172,000	
		Average				170,500	0.75
-423°F	Long.		266,000	279,000	5.0	151,000	
	Long.		261,000	279,000	5.0	149,000	
		Average	263,500	279,000	5.0	150,000	0.54
-423°F	Trans.		264,000	277,000	-	157,000	
	Trans.		-	251,000	-	152,000	
		Average	264,000	264,000		154,500	0.59

Chemical Composition - 5.8Al-3.6Zr-0.87V-.02C-.024N_2-.0084H_2

TABLE 29

MECHANICAL PROPERTIES OF Ti-7Al-12 Zr ALLOY

(0.050" Sheet, Heat R-98321, Mill Annealed 1650°F, 1 Hr.)

Test Temp.	Direction		Smooth Tensile Properties: Yield Strength 0.2% Offset psi	Tensile Strength psi	% Elong.	Notched Tensile Strength psi	Notched/Unnotched Tensile Ratio
+78°F	Long.		134,000	146,000	11.0	179,000	
	Long.		133,000	142,000	10.5	179,000	
	Long.		132,000	141,000	10.5		
		Average	133,000	143,300	10.7	179,000	1.25
+78°F	Trans.		132,000	139,000	17.0	179,000	
	Trans.		132,000	138,000	20.0	180,000	
			132,000	138,500	18.5	179,500	1.30
-320°F	Long.		197,000	214,000	11.0	173,000	
	Long.		196,000	214,000	12.5	162,000	
		Average	196,500	214,000	11.8	167,500	0.78
-320°F	Trans.		194,000	209,000	15.5	190,000	
	Trans.		195,000	212,000	11.5	196,000	
	Trans.		194,000	212,000	14.5		
		Average	194,300	211,000	13.8	193,000	0.91
-423°F	Long.		241,000	252,000	6.5	131,000	
	Long.		239,000	251,000	5.0	150,000	
	Long.		234,000	249,000	-		
		Average	238,000	250,700	5.8	140,500	0.56
-423°F	Trans.		235,000	251,000	4.0	161,000	
	Trans.		225,000	247,000	5.0	151,000	
		Average	230,000	249,000	4.5	156,000	0.63

Chemical Composition - 7.0 Al-11.5Zr-.01C-.01N_2-.09O_2-.012H_2

TABLE 30

MECHANICAL PROPERTIES OF RS-140 TITANIUM ALLOY

Longitudinal tests from ¼" plate, heat number R-11730.
Chemical composition — 0.031C, .010N_2, 4.90Al, 1.05Fe, 2.70Cr.

Condition	Test Temperature	Yield Strength 0.02% Offset psi	Tensile Strength psi (1)	Elong. %	% R. A.	V-Notch Charpy Impact Ft. Lbs. (2)
Annealed 1425°F, 1 hr. air cooled	+70°F	147,300 (3)	157,900	15.9	43.6	27.5 (4)
	-320°F	234,700 (4)	244,100	13.1	18.8	7.7 (4)
Heat Treated, 1450°F, 1 hr. water quenched,	+70°F	163,500 (4)	184,000	7.7	13.3	4.0 (4)
900°F, 6 hrs. air cool	-320°F	256,000 (4)	269,900	2.2	4.0	3.4 (4)

(1) Tensile test specimens were 0.113" diameter round shank, with 0.45" gage length.

(2) V-Notch Charpy impact specimens were twice standard width (0.788"), ½ standard thickness (0.197"), and ½ standard notch depth (0.039"), but with standard notch contour.

(3) Average of 5 tests.

(4) Average of 2 tests.

TABLE 31

MECHANICAL PROPERTIES OF B 120 VCA Titanium ALLOY

(0.250" Plate - Heat R-98103)

AS RECEIVED - Mill Annealed

Direction	Test Temperature, °F	Yield Strength 0.2% Offset, psi	Tensile Strength psi (1)	% Elong.	% R. A.	V-Notch Charpy Impact Ft. Lbs. (2)
Trans.	+70	140,600	150,400	18.8	54.0	6.0
Trans.	+70	140,400	148,200	17.2	53.0	-
Long.	+70	136,300	144,300	21.9	55.0	-
Long.	+70	137,700	145,800	18.8	54.0	-
Trans.	-320	-	251,700	1.5	1.5	1.4
Trans.	-320	-	239,800	1.5	0	1.5
Long.	-320	-	148,400	1.5	0.5	-
Long.	-320	-	197,000	1.5	1.0	-

Annealed at Convair-Astronautics, Heated to 1400°F, held 30 minutes, air cooled

Direction	Test Temperature, °F	Yield Strength 0.2% Offset, psi	Tensile Strength psi (1)	% Elong.	% R. A.	V-Notch Charpy Impact Ft. Lbs. (2)
Trans.	+70	139,200	144,100	21.9	54.0	10.0
Trans.	+70	137,600	144,900	17.2	52.0	9.9
Long.	+70	133,500	140,900	23.4	59.0	-
Long.	+70	134,200	141,500	21.9	56.0	-
Trans.	-320	-	214,900	1.5	0.5	1.3
Trans.	-320	-	246,300	4.6	1.5	1.5
Long.	-320	-	234,800	1.5	1.0	-
Long.	-320	-	265,800	1.5	0	-

NOTES:

(1) Tensile test specimens were 0.160" diameter round shank, with 0.64" gage length.

(2) V-Notch Charpy specimens were twice standard width (0.788"), ½ standard thickness (0.197"), and ½ standard notch depth (0.039"), but with standard notch contour.

Chemical composition - 12.5V-9.9Cr-5.3Al-.03C-.02N_2-.0184H_2

TABLE 32

MECHANICAL PROPERTIES OF 6Al-4V-Ti ALLOY

(0.75" Thick Forging - TMCA Heat No. and chemistry unknown)

Forging and Heat Treatment	Test Temp.	Yield Strength psi	Tensile Strength (1) psi	% Elong.	% R. A.	Notched (2) Tensile Strength psi	Notched/ Unnotched Tensile Ratio
Low finish forging temperature, air cooled,	+78°F	176,800	187,800	10.9	37.3	-	-
heated to 1725°F, 1 hr., water quenched, 1050°F, 3 hrs., air cooled.	-320°F	238,000	253,400	8.7	33.9	254,000	1.00
Forged at 1850°F, air cooled, heated to 1725°F, 1 hr., water quenched, 1050°F, 3 hrs.	+78°F	143,300	172,500	10.0	15.0	-	-
air cooled.	-320°F	239,700	253,600	3.8	7.4	236,500	0.93

(1) Standard 0.252" diameter tensile test specimen, 1.0" gage length.

(2) Notched tensile specimen, 0.283" diameter away from notch, circumferentially notched to diameter under notch of 0.200", 60° angle notch, root radius .0025", Stress Concentration, K_t=6.3

TABLE 33

Properties of Welded Joints in 5/16" 6Al-4V-Ti Alloy Plate.
Heli-arc Butt Welds, "V" Joints, Welds Completed with 4 Passes of Filler Wire.

Test	Stress Relieved			Heat Treated		
	6Al-4V Filler Wire	3.5Al-2.5V Filler Wire	Ti75A Filler Wire	6Al-4V Filler Wire	3.5Al-2.5V Filler Wire	Ti75A Filler Wire
Tensile Strength, +70°F, weld machined flush	139,400 139,500	127,600 128,400	101,800 98,280	171,200 168,300	147,200 139,400	115,700 119,800
Tensile Strength, +70°F, weld not machined	141,700 140,700	136,800 137,500	129,200 125,800	173,900 173,500	170,600 166,000	132,700 139,900
Tensile Strength, -320°F, weld machined flush	217,600	198,400 203,800	168,700 173,300	248,000 246,300	209,500 180,600	134,200 117,100
Tensile Strength, -320°F, weld not machined	220,200 221,800	219,300 219,400	185,000 195,700	249,500 251,000	232,500 228,600	157,800 157,200
% Elong., +70°F, weld machined flush	11.0 11.0	4.0 3.0	3.0 3.0	4.0 4.5	3.5 2.5	2.0 1.5
% Elong., +70°F, weld not machined	13.5 12.5	14.5 8.5	5.0 4.5	12.0 12.0	5.0 4.0	3.0 4.0
% Elong., -320°F, weld machined flush	11.5	3.5 2.5	3.0 2.5	2.0 2.0	1.5 2.0	1.0 1.0
% Elong., -320°F, weld not machined	17.0	28.5	4.0 4.5	3.0 7.0	4.5 3.5	2.0 3.0
V-Notch Charpy, +70°F, ft. lbs.	17.0 10.0	21.5 22.0	25.9 27.4	10.0 8.0	23.0 20.8	6.0 7.0
V-Notch Charpy, -320°F, ft. lbs.	7.4 6.2	10.5 10.8	16.7 13.5	4.0 5.1	10.5 13.5	5.0 4.0

NOTES:

Stress relieved - 1300°F - 1 hr. at temp. air cooled, after welding.

Heat treated - 1725°F - 1 hr. at temp., water quenched, aged at 1050°F - 2 hrs., air cooled, after welding.

Tensile test specimens - Fed. Std. 151, Type F2, flat test specimen, weld transverse to axis.

V-Notch Charpy test specimens - Twice standard width, half standard thickness, ½ standard depth of notch; notched in weld metal.

TABLE 34

MECHANICAL PROPERTIES OF HEAT TREATED Ti-6Al-4V HEMISPHERICAL FORGINGS, 1/2" to 3/4" Wall Thickness

Test Temp.	Direction With Respect to Grain Flow	Yield Strength psi	Tensile Strength psi	% Elong.	% R.A.	V-Notch Charpy(5) ft. lbs.
+70°F	Long.	127,700 (1)	146,200	27.0	53.5	14.0
+70°F	Long.	132,300 (1)	147,800	27.5	53.1	14.8
+70°F	Trans.	133,200 (1)	156,400	26.5	34.8	10.0
+70°F	Trans.	133,000 (1)	154,000	25.5	38.0	10.2
-320°F	Long.	225,300 (1)	232,800	11.1	30.0	9.5
-320°F	Long.	229,200 (1)	234,200	13.3	38.8	9.8
-320°F	Trans.	236,800 (1)	244,300	13.3	23.6	8.0
-320°F	Trans.	236,100 (1)	245,100	11.1	22.0	8.4
+70°F	Long.	137,000 (2)	156,100	16.2	52.6	17.7
+70°F	Long.	138,100 (2)	153,300	16.2	45.1	15.0
-320°F	Long.	228,700 (2)	236,400	11.1	36.4	10.0
-320°F	Long.	237,800 (2)	244,100	11.8	27.5	9.0
+70°F	Trans, base metal	140,800 (3)	153,500	10	27.9	-
-320°F	Trans, base metal	220,700 (3)	228,600	8	26.2	-
+70°F	Trans,	140,100 (4)	153,100	8	22.0	-
-320°F	Thru pressure weld	232,800 (4)	238,800	8	31.9	-

NOTES:

(1) Specimens from same forging, Fed. Std. 151, Specimen R4, 0.160" diam.

(2) Specimens from another forging, Fed. Std. 151, Specimen R4, 0.160" diam.

(3) Specimens from base metal of another forging, 0.113" diam., 0.625" gage length.

(4) Specimens with pressure weld transverse to middle of gage length. 0.113" diam., 0.625" gage length. Specimens machined after pressure welding and heat treating.

(5) Double width, half thickness of standard 0.394" square specimens, with half standard depth.

All forgings were heat treated. 1725° - 1750°F for 2-4 hours, water quenched, aged 1025° - 1050°F for 4-8 hours, air cooled.

TABLE 41

THERMAL CONDUCTIVITIES OF SOME THERMAL INSULATIONS AT VARIOUS TEMPERATURES, ALTITUDES, AND ATMOSPHERES

Specimen Identification			Altitude	Temperature (°F)	Atmosphere	Thermal Conductivity BTU/hr-ft² (deg. F per ft)
Stafoam		404	65,000'	- 43.5	Air	.028
Stafoam		406	65,000'	- 46.5	Air	.026
Stafoam		406	67,000'	- 95.0	Air	.018
Stafoam		1545.3	65,000'	- 77.0	Air	.022
Stafoam		1545.3	65,000'	- 95.0	Air	.019
		2974	65,000'	- 77.0	Air	.032
		2974	67,000'	- 95.0	Air	.017
Dow Q		907.1	65,000'	- 58.0	Air	.033
Dow Q		907.1	65,000'	+100	Air	.033
Dow Q		907.1	75,000'	- 95.0	Air	.019
Dow Q		907.1	25,000'	- 95.0	Air	.017
Dow Q		907.1	65,000'	- 95.0	Air	[illegible]
Dow Q		907.1	65,000'	+100	Air	.030
Dow Q		907.1	65,000'	-100	Air	.017
Dow Q		907.1	65,000'	+ 32.0	Air	.024
Dow Q		907.1	65,000'	+ 99.8	Air	.033
Dow Q		907.1	65,000'	+ 95.0	Air	.022
Nopco	B	607	0	- 89	Air	.040
Nopco	B	607	65,000'	- 69.5	Air	.019
Nopco	B	607	65,000'	- 66.5	Air	.025
Nopco	B	607	65,000'	- 95.0	Air	.020
Nopco	B	607	65,000'	- 95.0	Air	.020
Nopco	A	206	65,000'	- 74.0	Air	.029
Goodrich	H	327	65,000'	- 71.5	Air	.026
	PC	2?1	25,000'	- 95.0	Air	.019
Corefoam (1t)			25,000'	- 95.0	Air	[illegible]
Zenith		228	0	- 98.0	Air	.033
Zenith		231	0	-100	Air	.021
Zenith		246	0	- 97	Air	.032
Zenith		248	0	- 97	Air	.036
Zenith		230	0	- 95	Air	[illegible]
		570211.1	0	- 97	Air	.023
		570211.2	0	- 97	Air	.0?3
		570211.3	0	- 97	Air	.027
Stafoam		1102	0	+ 63	Air	.025
Stafoam		1102	0	+116	Air	.022
Stafoam		1102	0	+300	Air	.0?4
Dow Q		907.2	0	- 97.0	Air	[illegible]
Dow Q		907.2	0	+ 70.0	Air	.029
Metal Honeycomb			0	+ 70.0	Air	.033
Nopco	A	210	0	+100	Air	.031
Nopco	A	210	0	+115	Air	.035
Nopco	A	210	0	0	Air	.027
Nopco	A	210	0	-100	Air	.021
Nopco	A	210	0	+175	Air	.033
Nopco	A	210	0	+125	Air	.028
Urethane			0	+ 75	He	.079

TABLE 41 (CONT'D)

THERMAL CONDUCTIVITIES OF SOME THERMAL INSULATIONS AT VARIOUS TEMPERATURES, ALTITUDES, AND ATMOSPHERES

Specimen Identification		Altitude	Temperature (°F)	Atmosphere	Thermal Conductivity BTU/hr-Ft² (deg. F per ft)
Urethane		0	+ 75	Air	.019
Urethane		0	-100	Air	[illegible]
Urethane		0	-100	He	.039
Urethane		0	0	Air	[illegible]
Urethane		0	0	He	.054
Urethane		0	-50	He	[illegible]
Urethane		0	+150	He	[illegible]
Urethane		0	+150	He	[illegible]
Urethane		0	+ 75	He	[illegible]
Urethane		0	+150	He	[illegible]
Urethane		0	+120	Air	.031
Urethane		0	+150	Air	[illegible]
Urethane		0	+150	Air	.025
Urethane		0	+ 75	Air	.028
Urethane		0	+ 75	Air	[illegible]
Urethane		0	+ 75	Air	[illegible]
Urethane		0	+ 75	Air	[illegible]
Urethane		0	- 50	Air	.028
Urethane		0	- 50	Air	.028
Urethane		0	0	Air	[illegible]
Urethane		0	0	Air	[illegible]
Urethane		0	+ 75	He	.026
Urethane		0	+ 75	He	[illegible]
Urethane		0	+ 75	He	.029
Urethane		0	- 50	He	.036
*Nopco	B 610	25,000'	- 95.0		
*Nopco	B 610	25,000'	+100		
*Nopco	B 610	25,000'	+200		

*
NOTE: 1. No thermal conductivities were determined for sample #B610 since it shrunk badly at 100°F and 200°F.

TABLE 42

IMPACT SENSITIVITY OF LIQUID OXYGEN-LUBRICANTS

Material	Supplier	Impact Level (ft-lbs)	Detonations	[illegible]
"Liquid Oxygen" Safe	Redel Inc.	70	57	[illegible]
"Liquid Oxygen" Safe Batch 3	-	60	13	[illegible]
"Liquid Oxygen" Safe Batch 7	-	40	22	[illegible]
Synthetic Anti-Seize Grease Anderol L-795	Leigh Chemical Co.	70	3	[illegible]
Anderol L-751	Leigh Chemical Co.	70	3	[illegible]
Lubriplate-Aero	Fiske Bros. Refining Co.	70	3	[illegible]
Lubriplate- Low Temp.	" "	70	3	[illegible]
1080 Mica Grease	Ohio Grease Co.	70	3	[illegible]
Fel-Pro C-5 Hi-Temp Thread Lubricant	Felt Grease Co.	70	3	[illegible]
High Purity Goop	Crawford Fittings Co.	70	0	[illegible]
Blue Goop	" "	70	3	[illegible]
Cellulube 220	Celanese Corp. of America	40	4	10
Dixseel	Dixon Corp.	70	1	10
Dixseel (oven dried 1.5 hrs. at 150°C)	Dixon Corp.	70	4	[illegible]
Kano Pyrolube	Kano Laboratories	70	3	[illegible]
Dag Dispersion No. 224	Acheson Colloids Co.	70	0	[illegible]
Flourolene C	Nuclear Products Co.	70	0	[illegible]
Arochlor 1254	Monsanto Chemical Co.	70	5	11
Arochlor 1260	" "	70	7	10
Hoke Slic Seal (air dried)	Hoke, Inc.	70	1	[illegible]
Hoke Slic Seal (oven dried) 180°C, 10 min	Hoke, Inc.	70	0	[illegible]
Q Seal	Quigley Co., Inc.	70	0	[illegible]
Fluorolube FS-5 Oil	Hooker Electrochemical Co.	60	0	[illegible]
Drilube Type 209	Drilube Co.	60	0	[illegible]
Ready Lube No. 2	Redel, Inc.	60	[illegible]	[illegible]
Compound No. 265	Valley Products	60	[illegible]	[illegible]
Liquid Oxygen Spec. N. A. 2-20302	Rocketdyne	60	6	[illegible]
		40	4	[illegible]
		20	2	20
Anti-Seize Compound #250	Armite Lab.	60	3	[illegible]
Ucon Lubricant LB-165	Union Carbide	40	[illegible]	[illegible]
Ready Lube No. 2, Batch 9	-	60	2	[illegible]
Ready Lube No. 2, Batch 4	-	70	57	[illegible]
Synthetic Anti-Seize Grease	-	70	3	[illegible]
"Rectorseal" RS-15 Thread Compound	Rector Well Equipment Co.	70	4	[illegible]
Seal Rite No. 5 (Dried at room temp. for 60 hrs.)	Mackson's Co.	70	[illegible]	[illegible]
Mogul Taper Valve Lubricant	Metallizing Co. of America	70	[illegible]	[illegible]
Mogul Taper Valve Lubricant (oven dried, 150°C, 1 wk.)	" "	70	[illegible]	[illegible]
Fused Teflon	E. I. Dupont de Nemours & Co. Inc.	70	0	20
Halo-carbon 14-25TF25	Halo-carbon Products	70	0	20

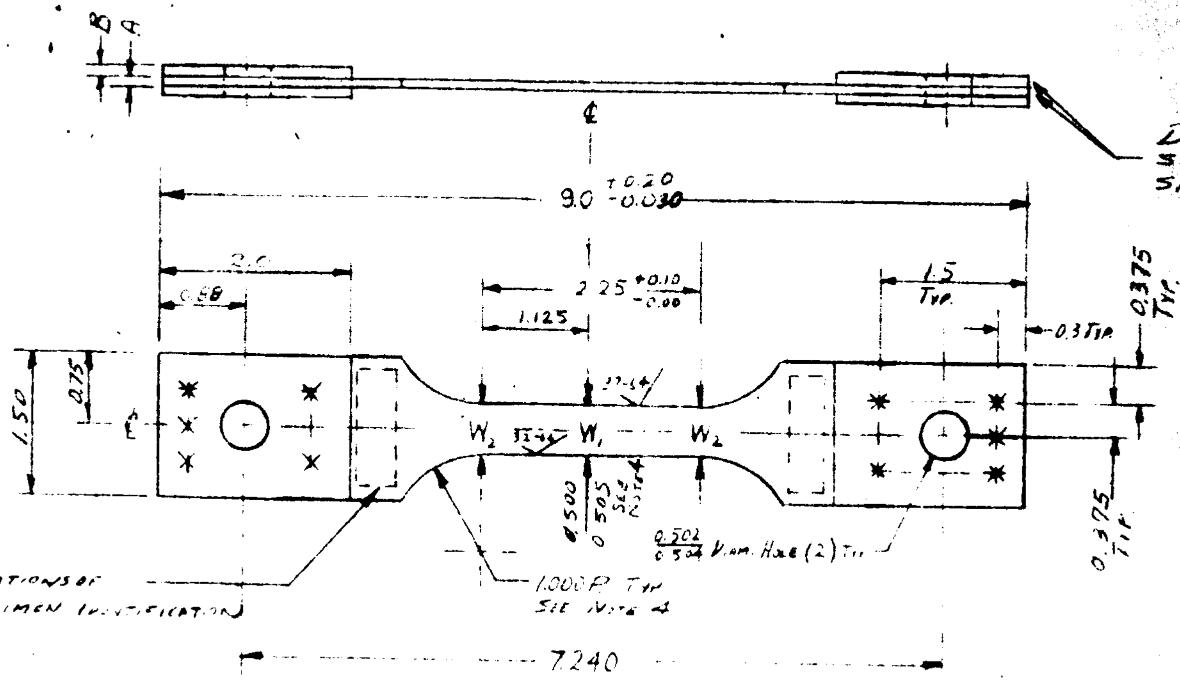
TABLE 42 (CON'T)

IMPACT SENSITIVITY IN LIQUID OXYGEN-LUBRICANTS

Material	Supplier	Impact Level (ft-lbs)	Detonations	[illegible]
Halo-carbon 25-20M	Halo-carbon Products	70	0	[illegible]
Houghton Safe Oil 1120	F. E. Houghton Co.	70	5	[illegible]
Houghton Safe Oil 1055	" "	70	4	[illegible]
Houghton Safe Oil 620	" "	70	2	[illegible]
FC 75 Fluorocarbon Ether	Minnesota Mining & Manufacturing Co.	70	0	[illegible]
Graphite	-	60	No Reaction	

REVISIONS

EFF ON	INCORP	SYM	DESCRIPTION	DATE



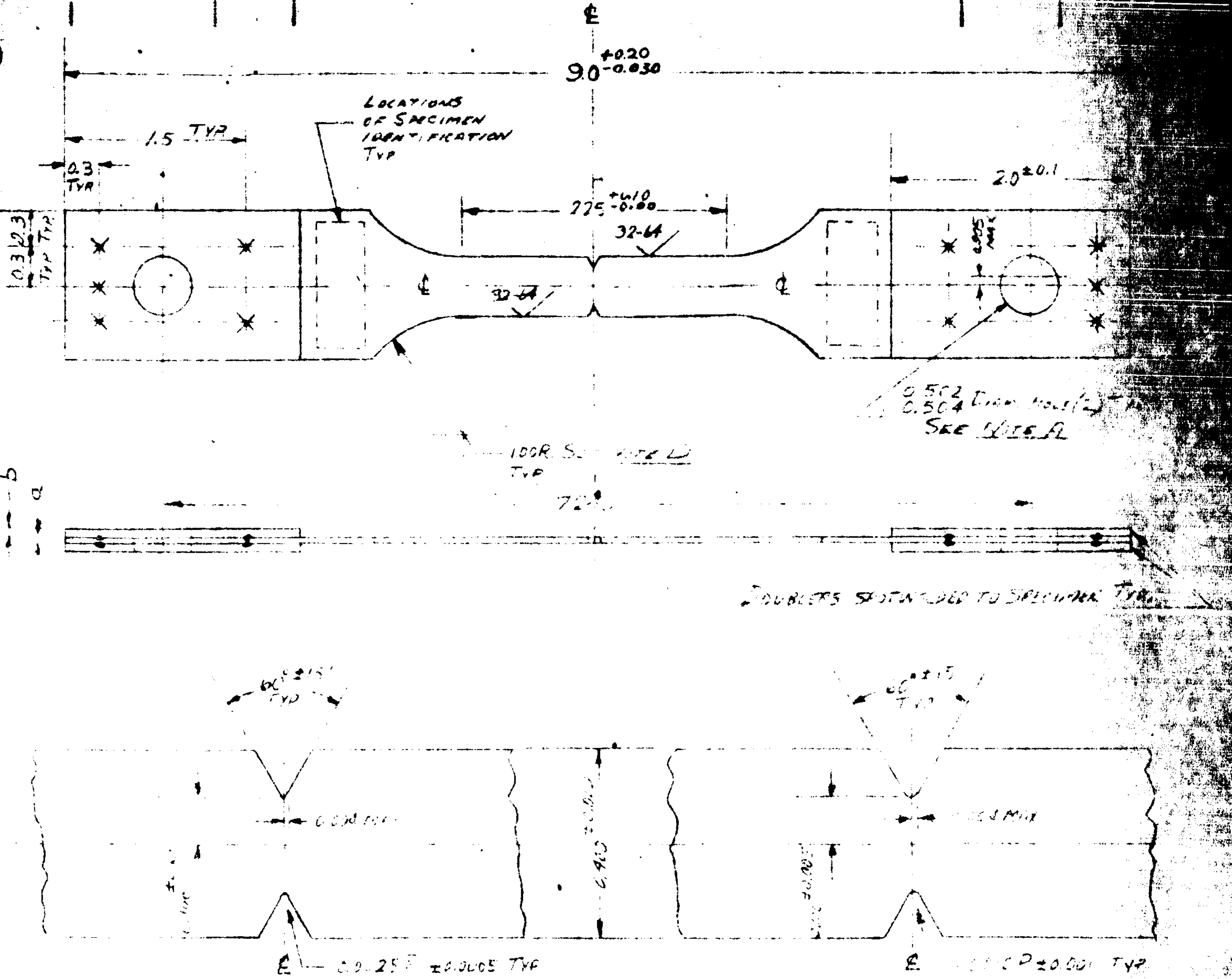
	Specimen Thickness, A	Doubler Thickness, B	Specimen Material	Doubler Material
	Up to 0.030	0.025		

See Notes on Sheet 2 of 2

Unless otherwise specified dimensions in inches tolerances on	All Machine Surfaces 64-125 Unless Otherwise Specified	SPECIFICATION CONTROL DRAWING	CONVAIR ASTRONAUTICS
.XX ±0.03 .XXX ±0.010 Angles ±0°30'	Corp: Mat'l. Research 575-2		Convair is a division of General Dynamics Corporation San Diego, California
	Chk: C... ...rood 3/11/59	D.P. NO. Sheet 1 of 2	DWG Size A — Flat Tensile Specimen (Standard)

REVISIONS

ZONE	INCORP	SYM	DESCRIPTION	DATE



Type "A" Notch – $\frac{A}{r}$ = 40 (32-52)
See Notes B & C

Type "B" Notch – $\frac{A}{r}$ = 10 (9.6-11.1)
See Notes B & C

See Notes on Sheet 2 of 2

Specimen Thickness, a	Doubler Thickness, b	Specimen Material	Doubler Material
Up to 0.030	0.025		

All Machine Surfaces 64-125 Unless Otherwise Specified

QUALIFICATION CONTROL DRAWING

CONVAIR-ASTRONAUTICS
CONVAIR IS A DIVISION OF GENERAL DYNAMICS CORPORATION
SAN DIEGO, CALIFORNIA

CKD

SHEET 1 of 2

SIZE A

Notched Tensile Specimen

Figure 3 -"Thermal Conductivity of Polycel 420"

disgarded by writers.

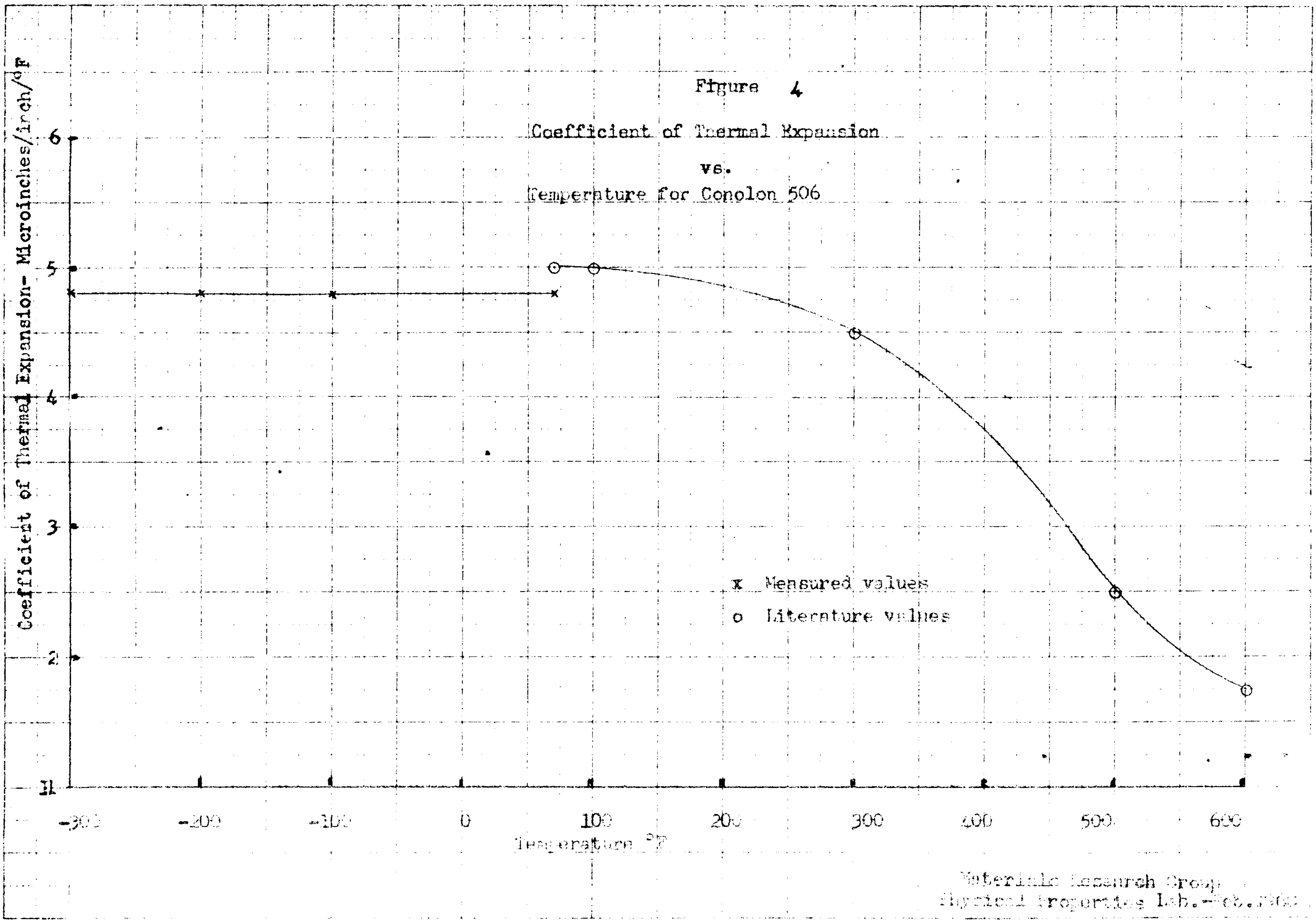


Figure 4

Coefficient of Thermal Expansion

vs.

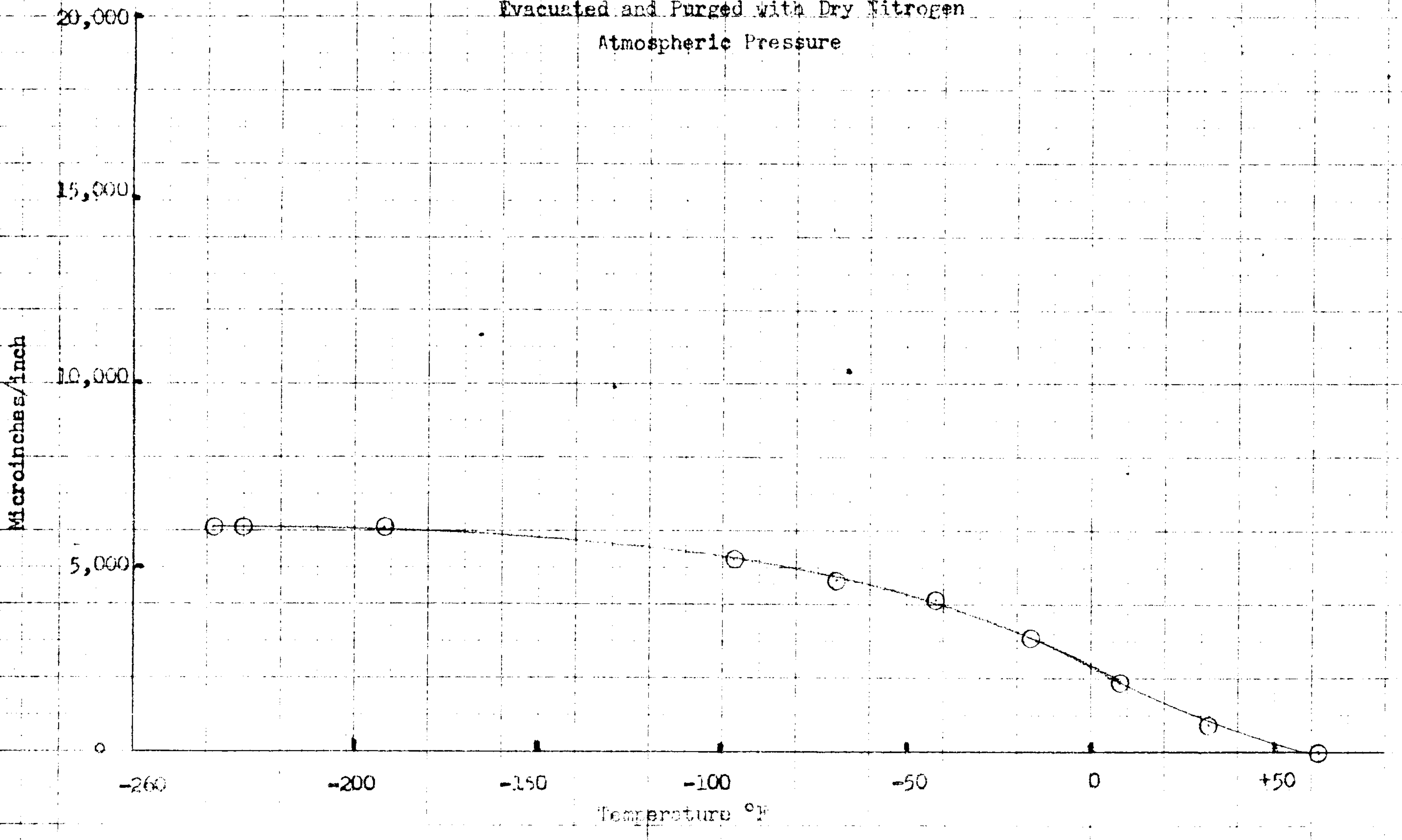
Temperature for Conolon 506

Figure 5

Expansion of Polycel 420

Evacuated and Purged with Dry Nitrogen

Atmospheric Pressure

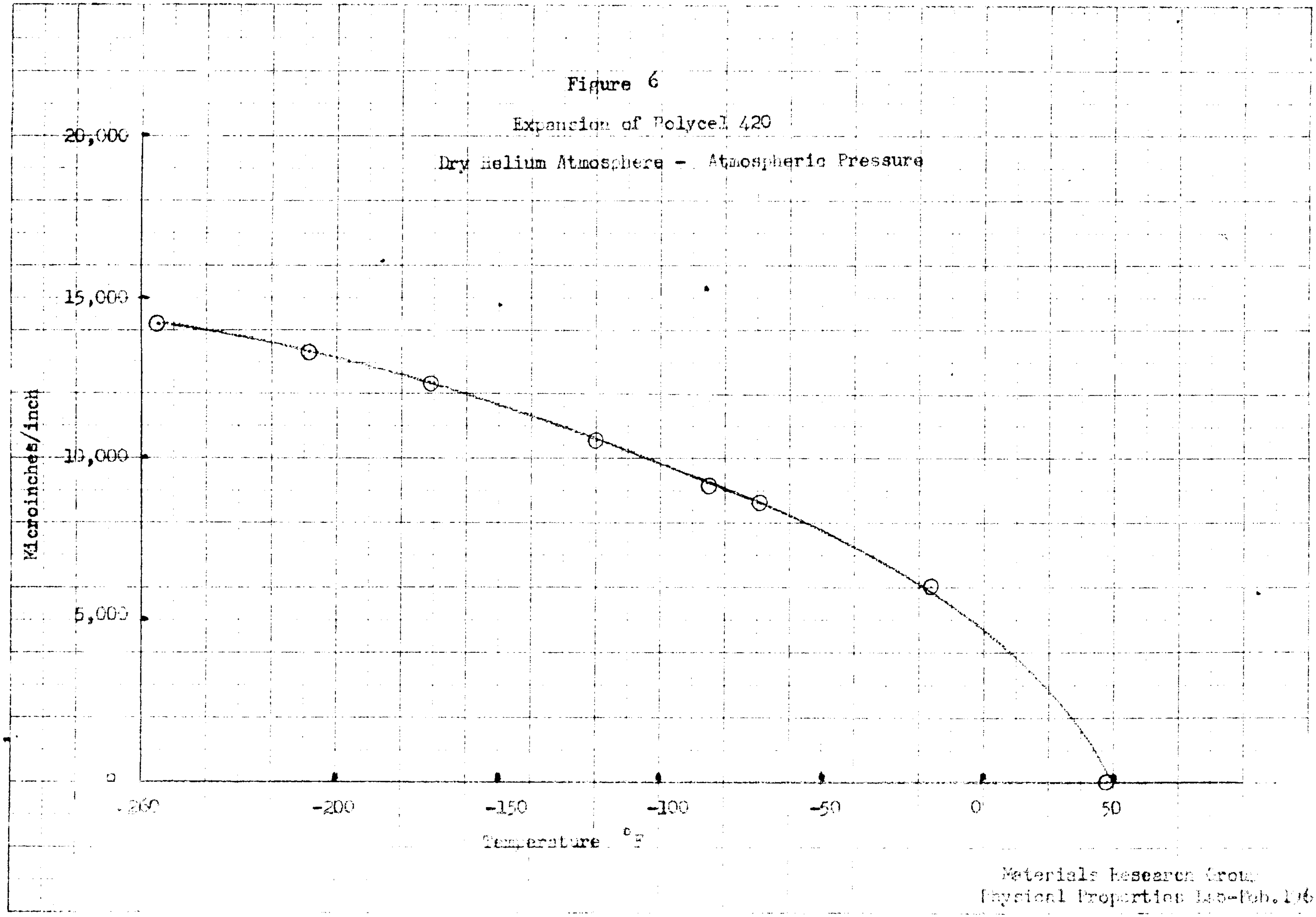


Materials Research Group
Physical Properties Lab. - Feb. 1960

Figure 6

Expansion of Polycel 420

Dry Helium Atmosphere - Atmospheric Pressure



Materials Research Group
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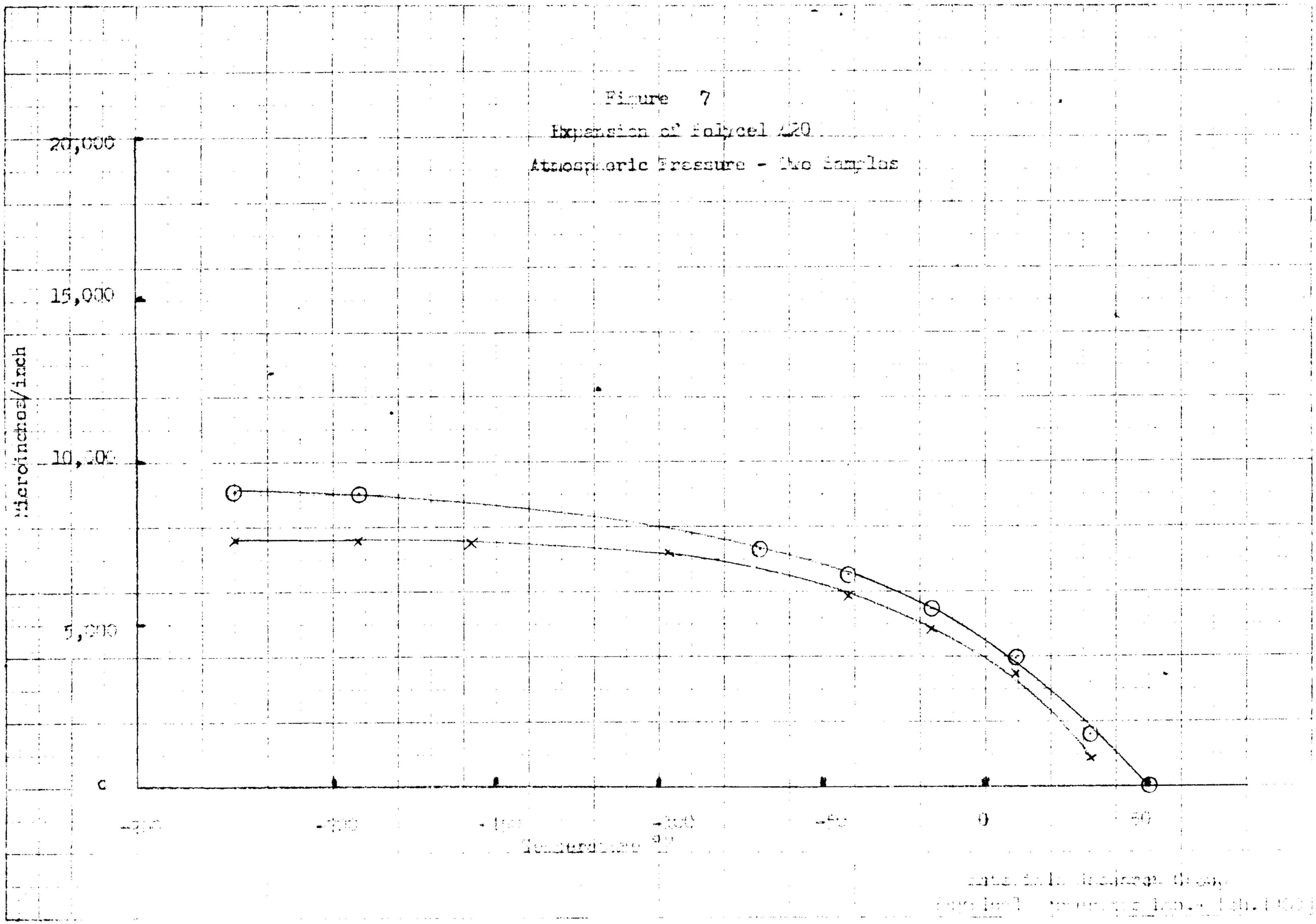


Figure 7

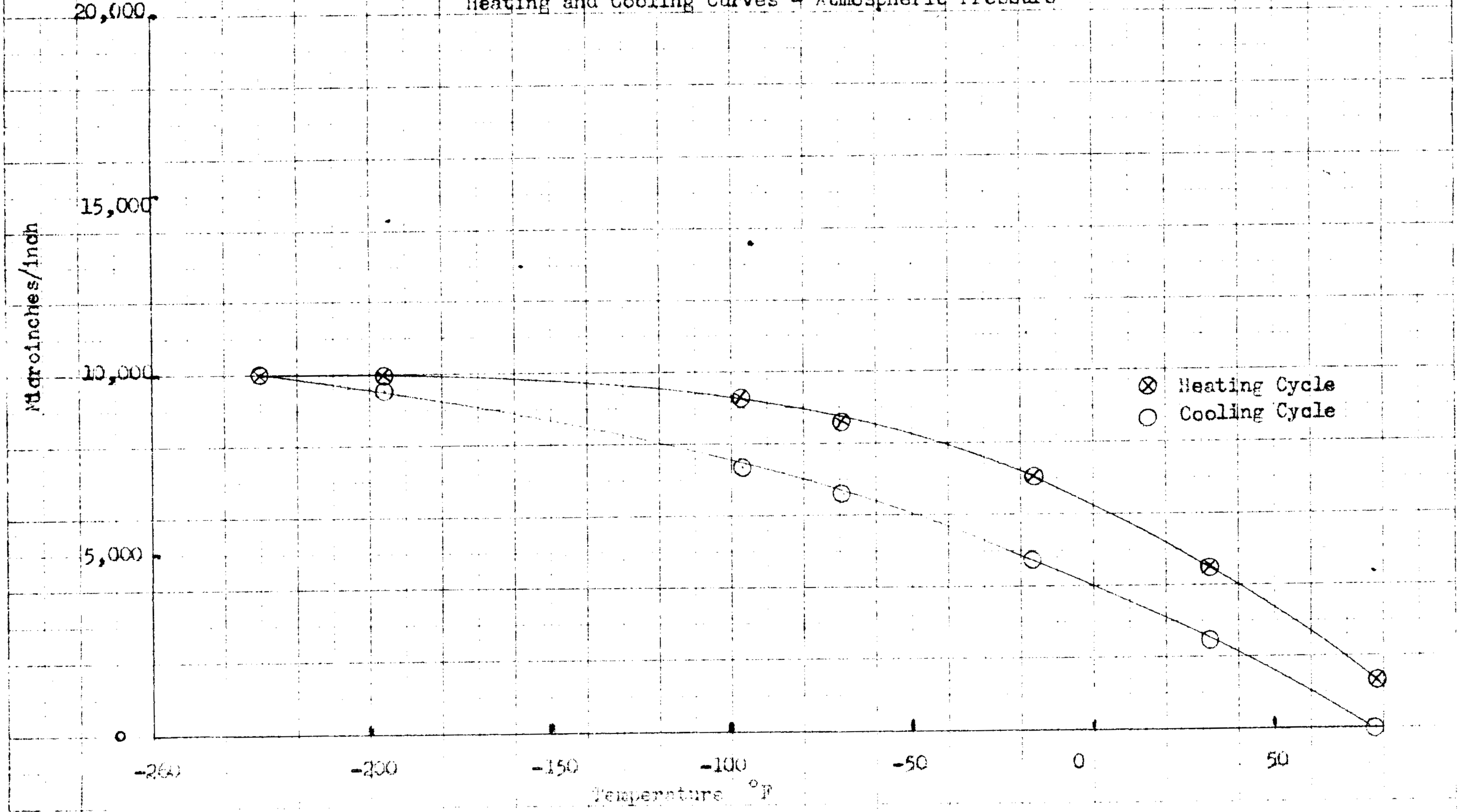
Expansion of Polycel 420

Atmospheric Pressure - Two Samples

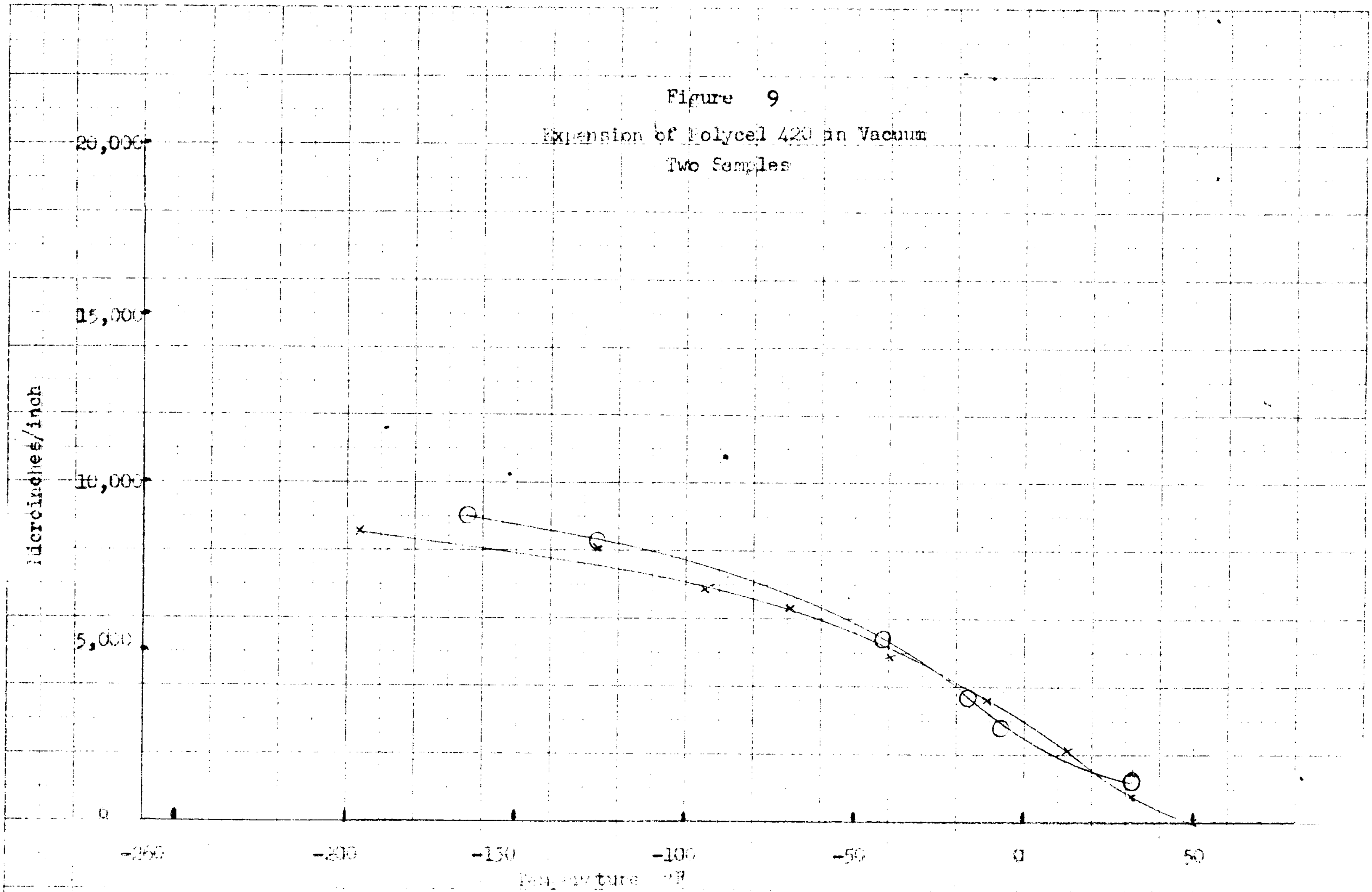
Figure 8

Expansion of Polycel 420

Heating and Cooling Curves - Atmospheric Pressure



Materials Research Group
Physical Properties Lab. - Feb. 1960



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Physical Properties Lab.

APPENDIX A

CHEMICAL ANALYSIS AND HISTORY OF STAINLESS STEELS

	301[A] 3/4 HD	301[B] Full HD	301, Extra Full Hard .013[C]	301, Extra Full Hard .023[D]	301, Extra Full Hard .032[E]	301, 42%[F] Cold Roll	301, 78%[G] Cold Roll	302, 40%[H] Cold Roll	302, 60%[I] Cold Roll	310, 40 60 & 75% Cold Roll[J]	304[K] ELC	301-N[L] Extra Full Hard
Cr	17.74	17.68	17.02	17.64	17.64	17.72	17.78	18.35	18.65	25.26	18.04	17.12
Ni	6.[illegible]7	7.29	7.17	7.11	7.11	7.32	7.35	8.96	8.32	19.58	10.39	6.29
C	.07	.06	.1[illegible]	.08	.08	.10	.09	.0[illegible]	.03	.040	.023	.10
Mn	.97	1.06	.[illegible]1	1.04	1.04	1.34	1.83	.64	.65	1.6[illegible]	1.54	.79
P	.026	.027	.026	.023	.023	.020	.032	-	-	-	.026	.027
S	.022	.025	.017	.014	.014	.011	.014	-	-	-	.011	.030
Si	.41	.41	.55	.64	.64	.48	.42	1.50	.[illegible]	.70	.66	.43
N												.125

SUPPLIER	[A]Washington	[B]Washington	[C]Washington	[D]Washington	[E]Washington	[F]Crucible	[G]Crucible	[H]Allegheny-Ludlum
GAUGE	.020	.016	.013	.023	.032	.015	.01[illegible]	.020
HEAT NO.	47654	56476	48175	48112	56760	133019	152573	327250
COIL NO.	36120	33468B	38358	36125	4[illegible]1[illegible]1	-	-	-

SUPPLIER	[I]A-L	[J]A-L	[K]Rodney Metals	[L]Washington
GAUGE	.020	.020	.012	.017
HEAT NO.	84204	84074	33251	31131
COIL NO.	-	-	-	Y27352